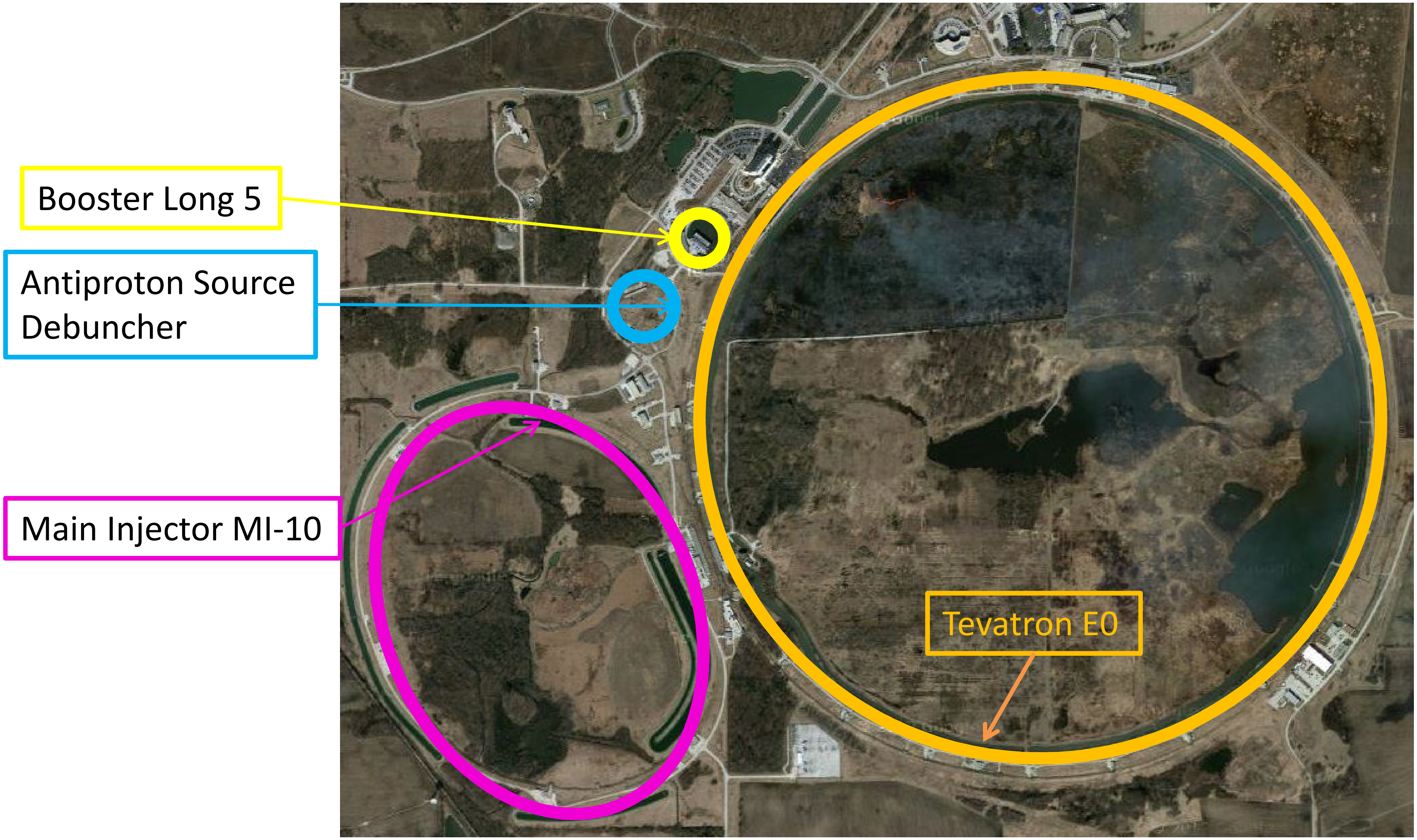
Instrumentation Department

# Status of Profile Monitors @ Fermilab

11 June 2013

Jim Zagel & Randy Thurman-Keup

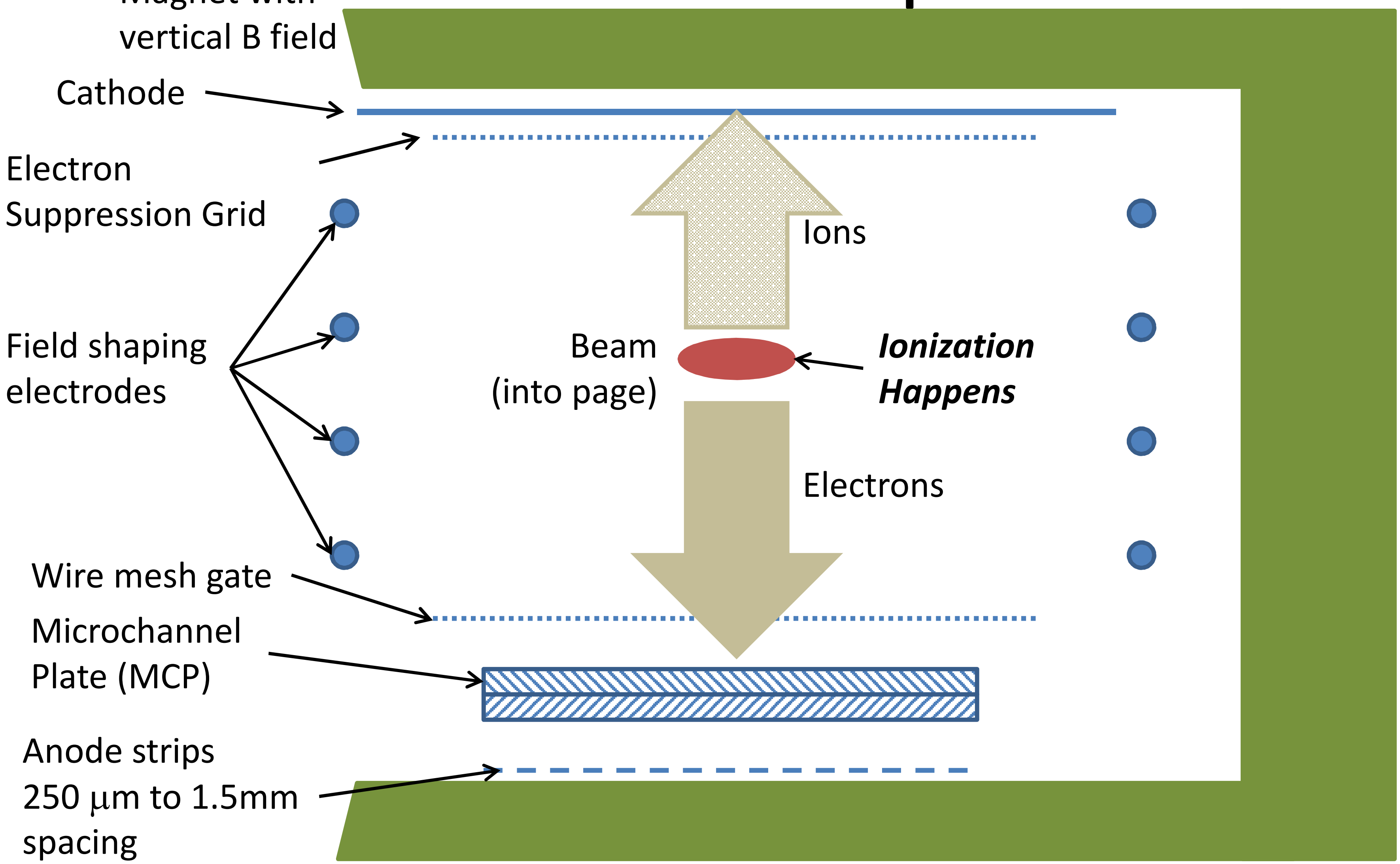
# IPM's in the Tev ERA



# IPM Basic Types

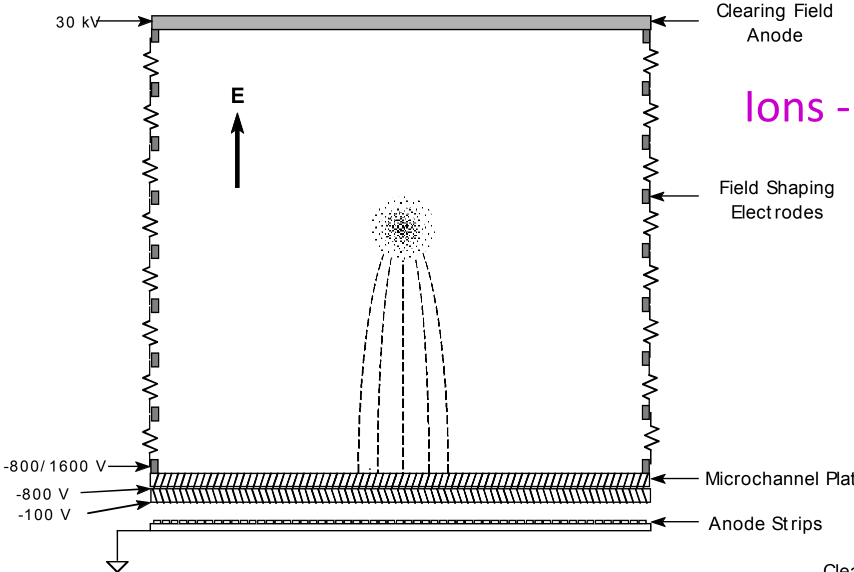
- Booster (400MeV – 8 GeV)
  - Electrostatic 10KV Clearing Field (Good at injection.)
- Main Ring Original (8 GeV -150GeV)
  - Electrostatic 30KV Clearing Field (Good at injection.)
- Recycler Ultra High Vacuum (8 GeV)
  - Electrostatic 30KV Clearing Field, e-11 Torr vacuum.
- Main Injector Mark-II (8 GeV -150GeV)
  - Permanent Magnetic Field 1KG and 10KV Clearing Field.
- Tevatron (150 GeV – 1 TeV)
  - Electro Magnet 1 KG and 10KV Clearing Field.

# IPM Concept

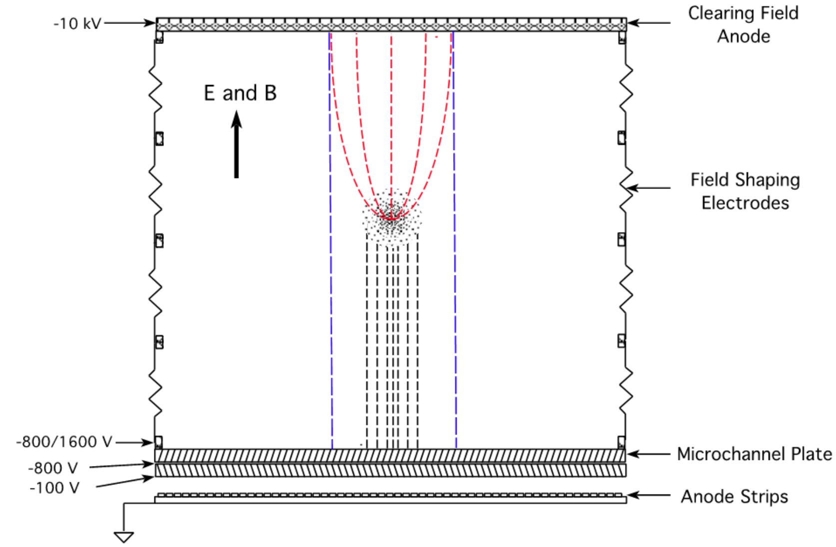

Magnet with
vertical B field
Cathode
Electron
Suppression Grid
Field shaping
electrodes
Wire mesh gate
Microchannel
Plate (MCP)
Anode strips
250 μm to 1.5mm
spacing
Ions
Beam
(into page)
*Ionization*
*Happens*
Electrons

# Why the Magnetic Field

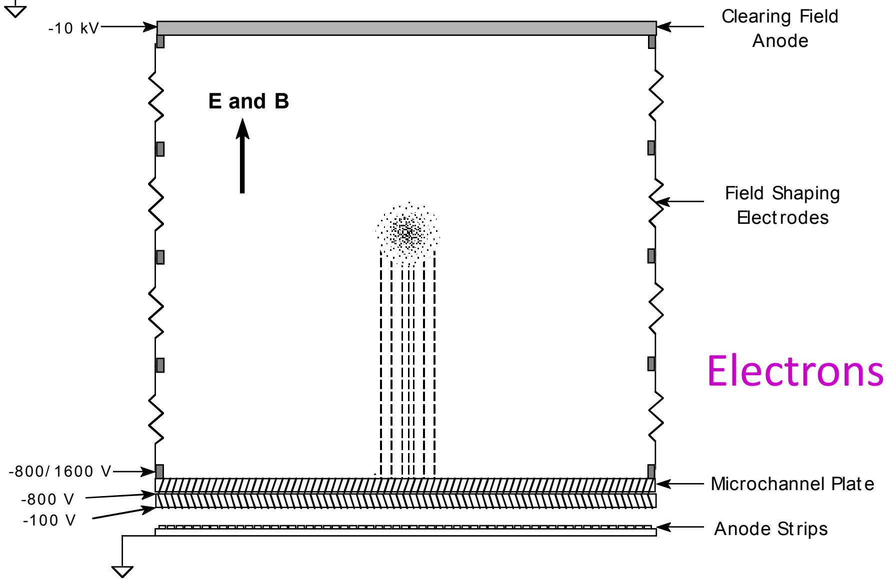
Ions - E field only




Ion / electron paths
with E and B field




Mark II Ion Profile Monitor
With Secondary Electrons
10/11/2010 jrz

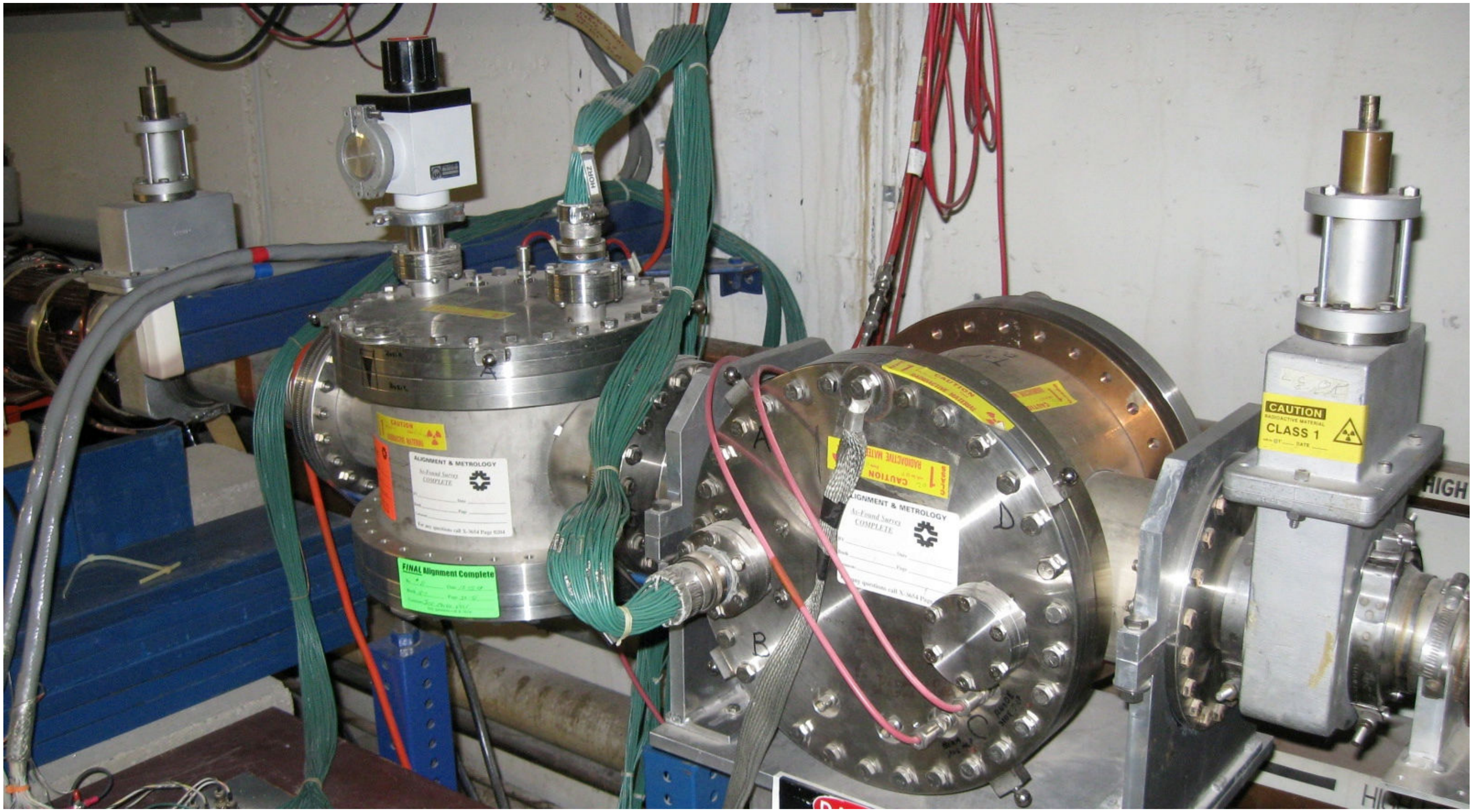



Electrons - E and B field

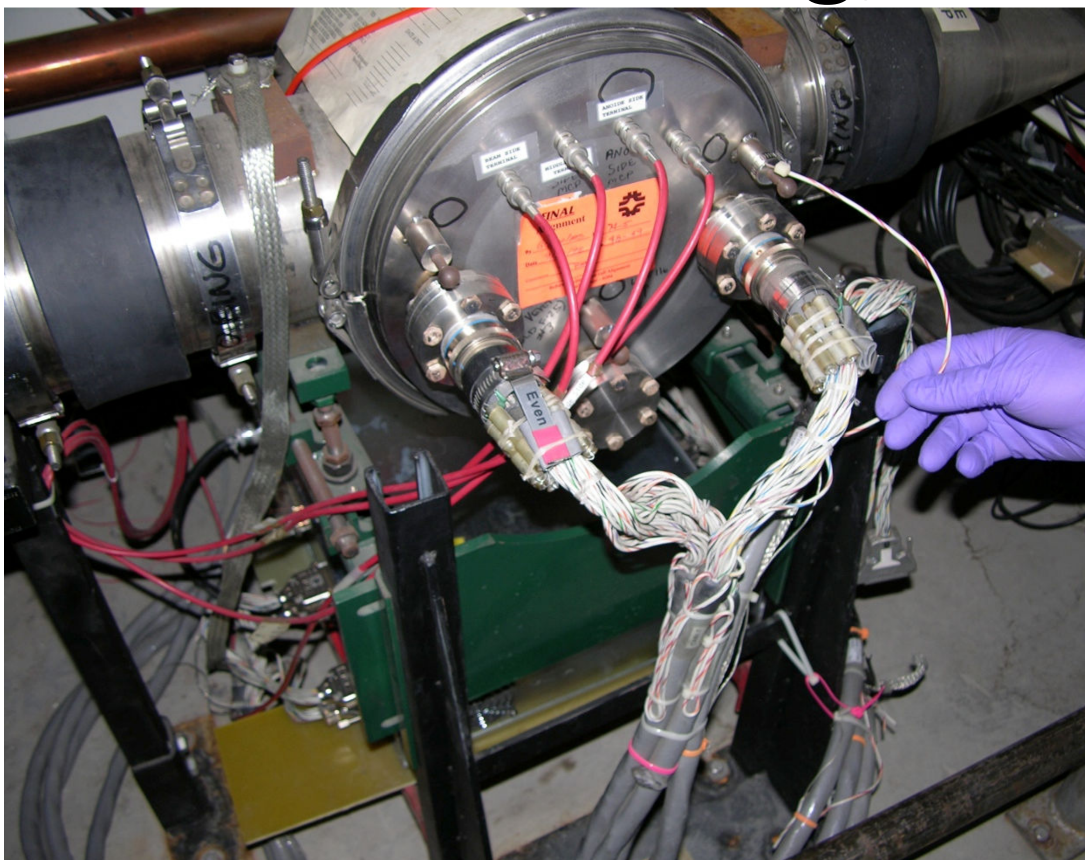
**Mark II Ion Profile Monitor**
**Vacuum Chamber Detail**
7/31/03 jrz

# Booster

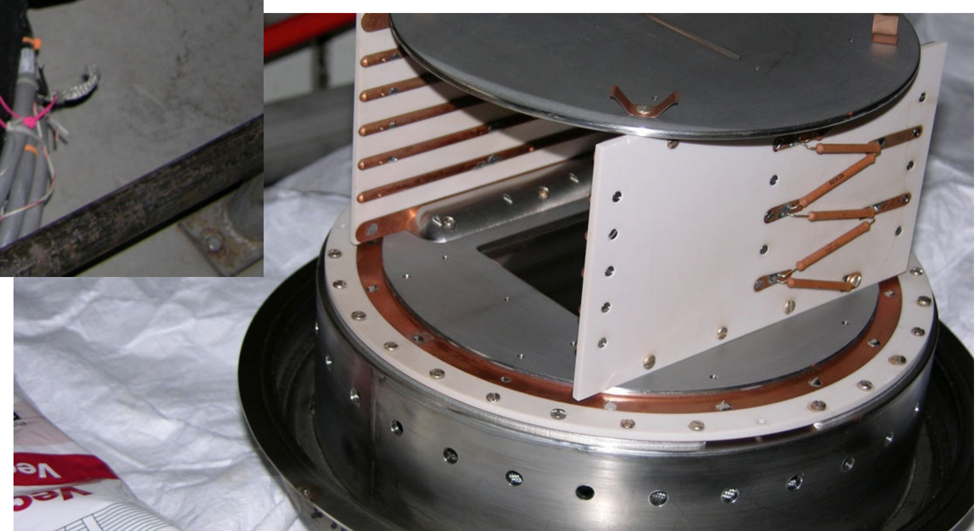
Horizontal and Vertical co-located in Long 5



# Main Ring/MI Original



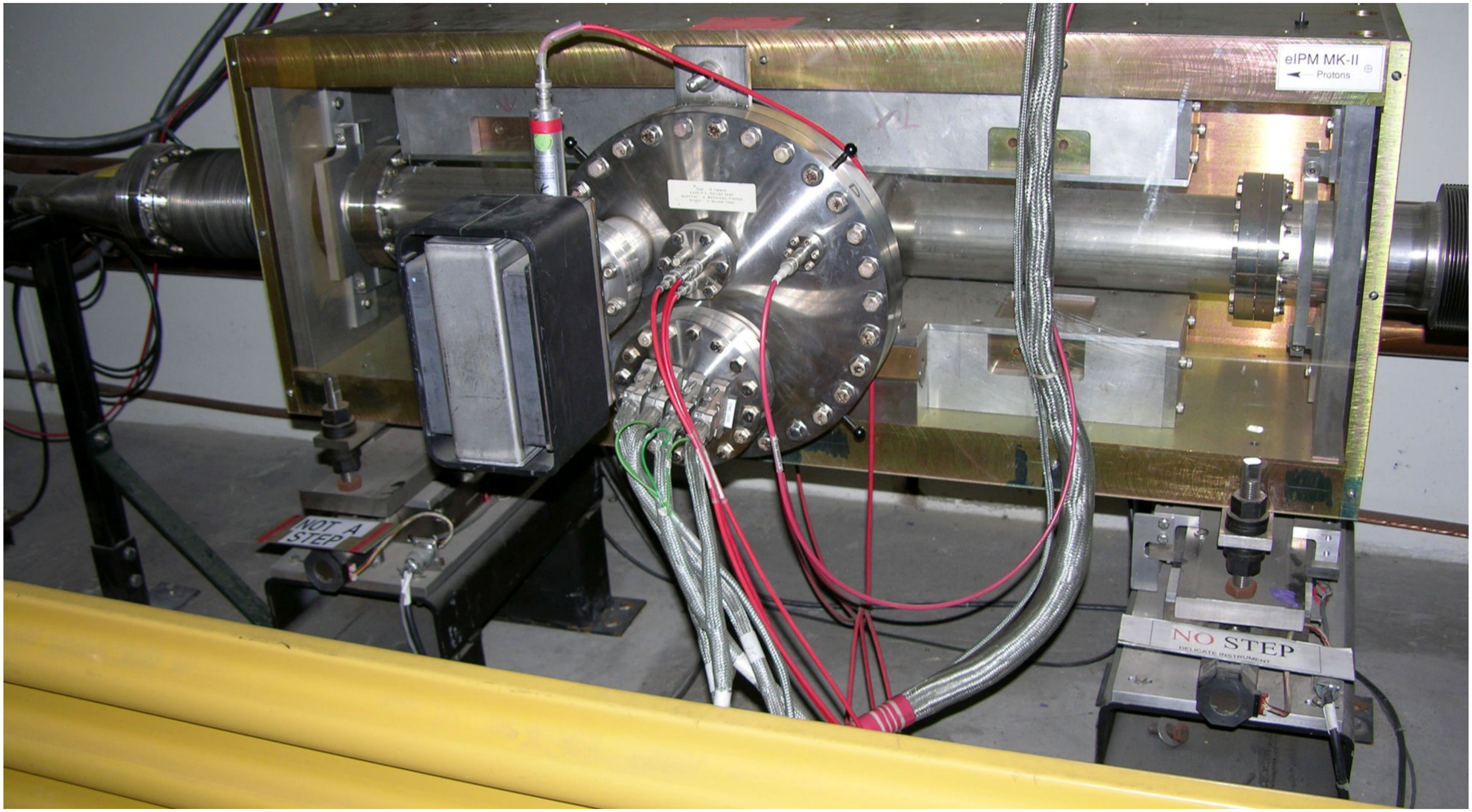

Vertical at Q103
Also a Horizontal at Q102



# Main Injector Mark-II

Horizontal Measurement Permanent Magnet at Q104

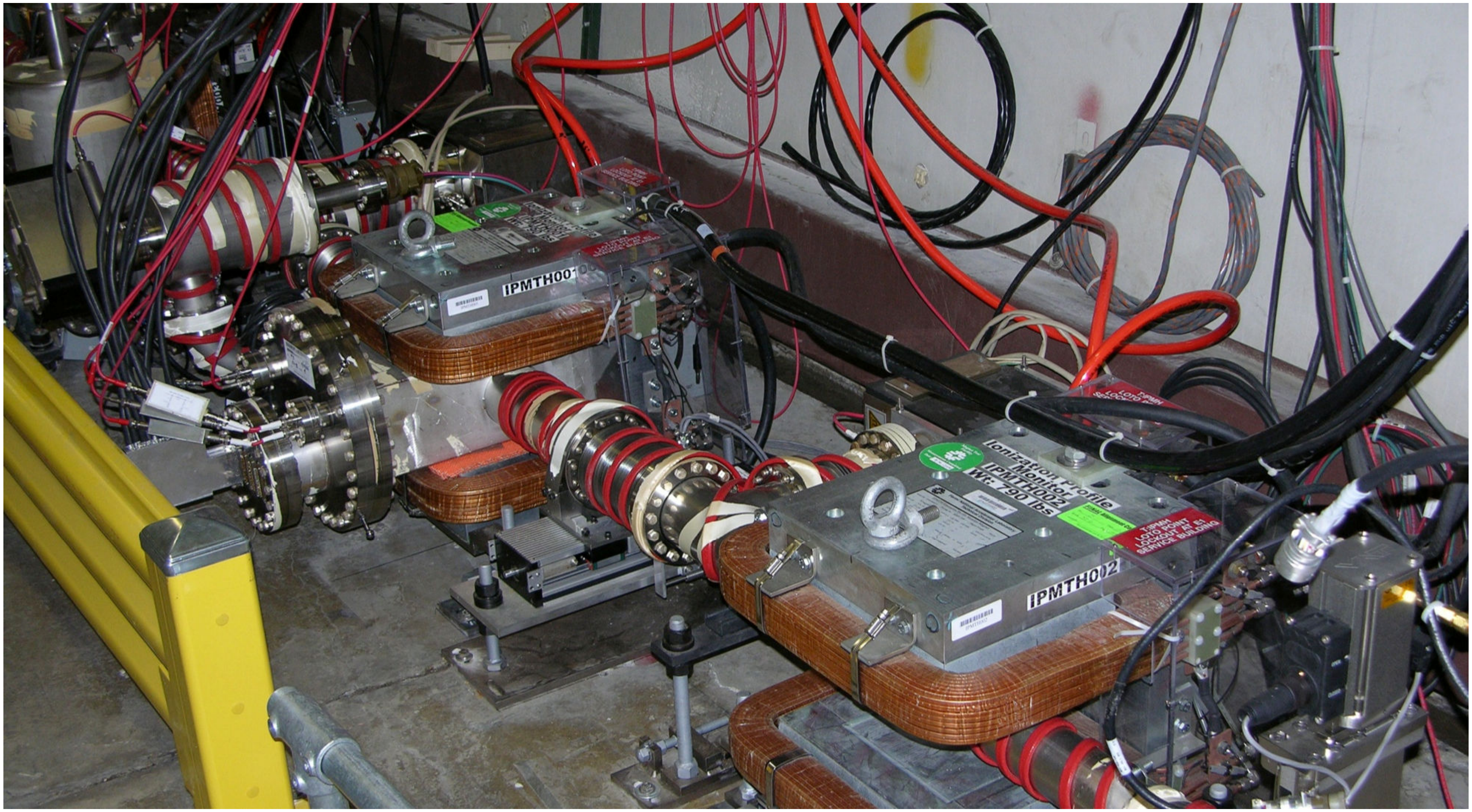
Independent up and downstream +/- 25mm in horizontal plane for alignment and MCP Exposure



# Tevatron

Measured 36 Proton and 36 Anti-Proton bunches per turn using QIE Chips in tunnel.

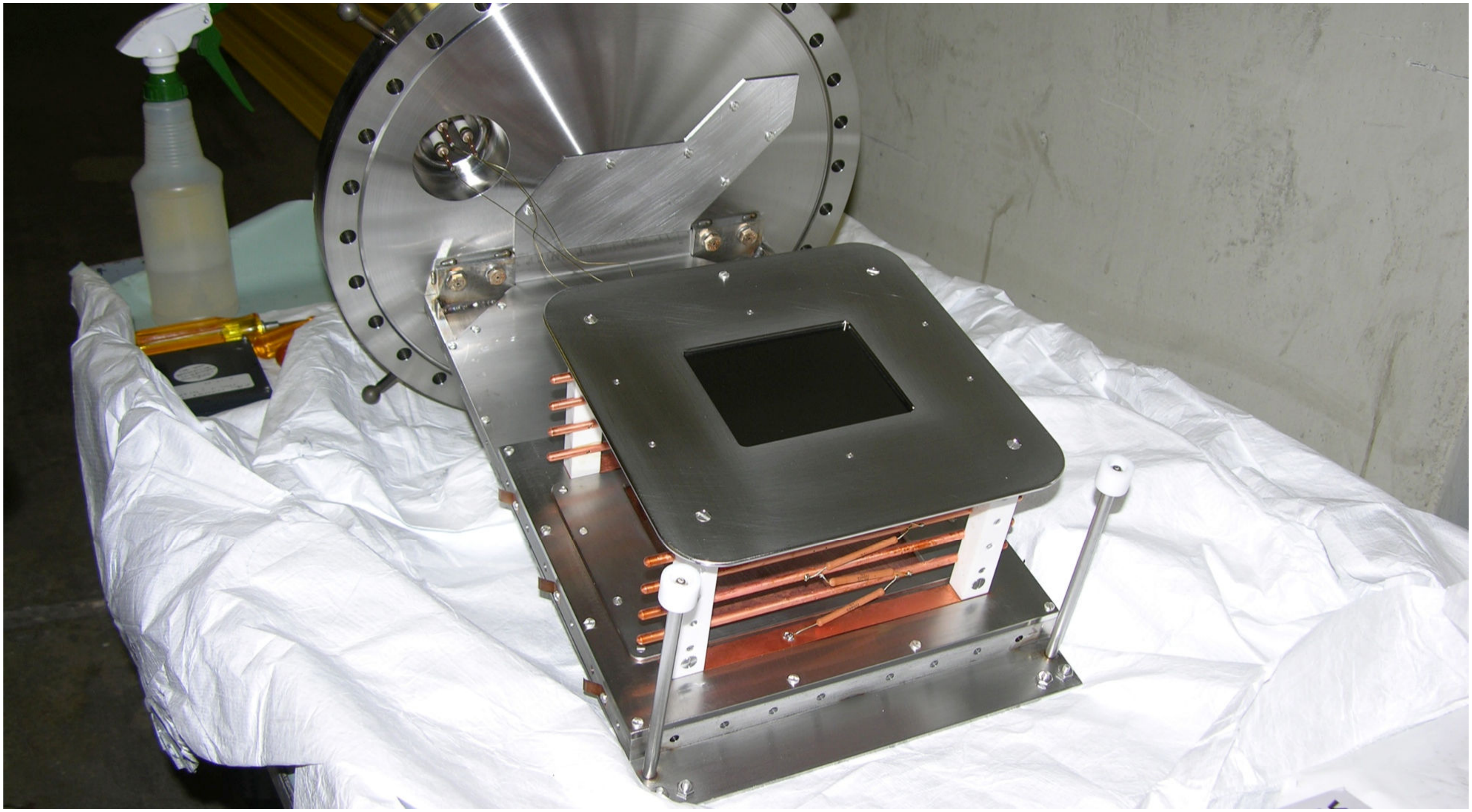
Horizontal Detector



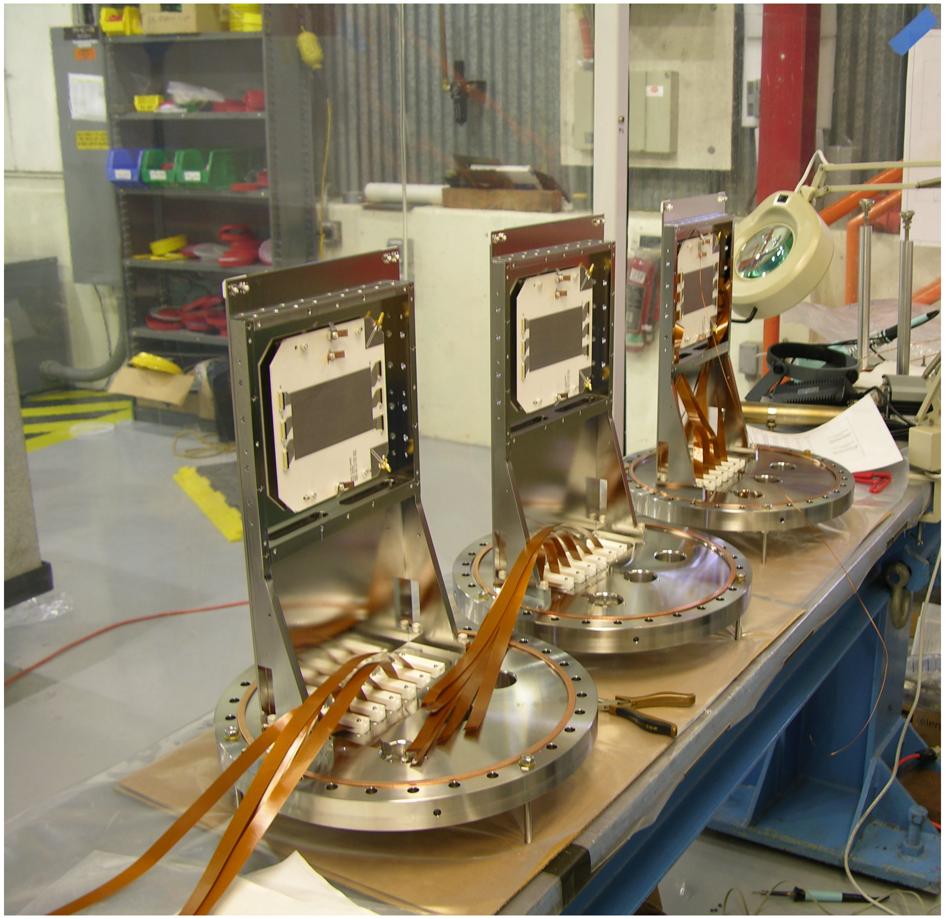

Horizontal Correction Magnet

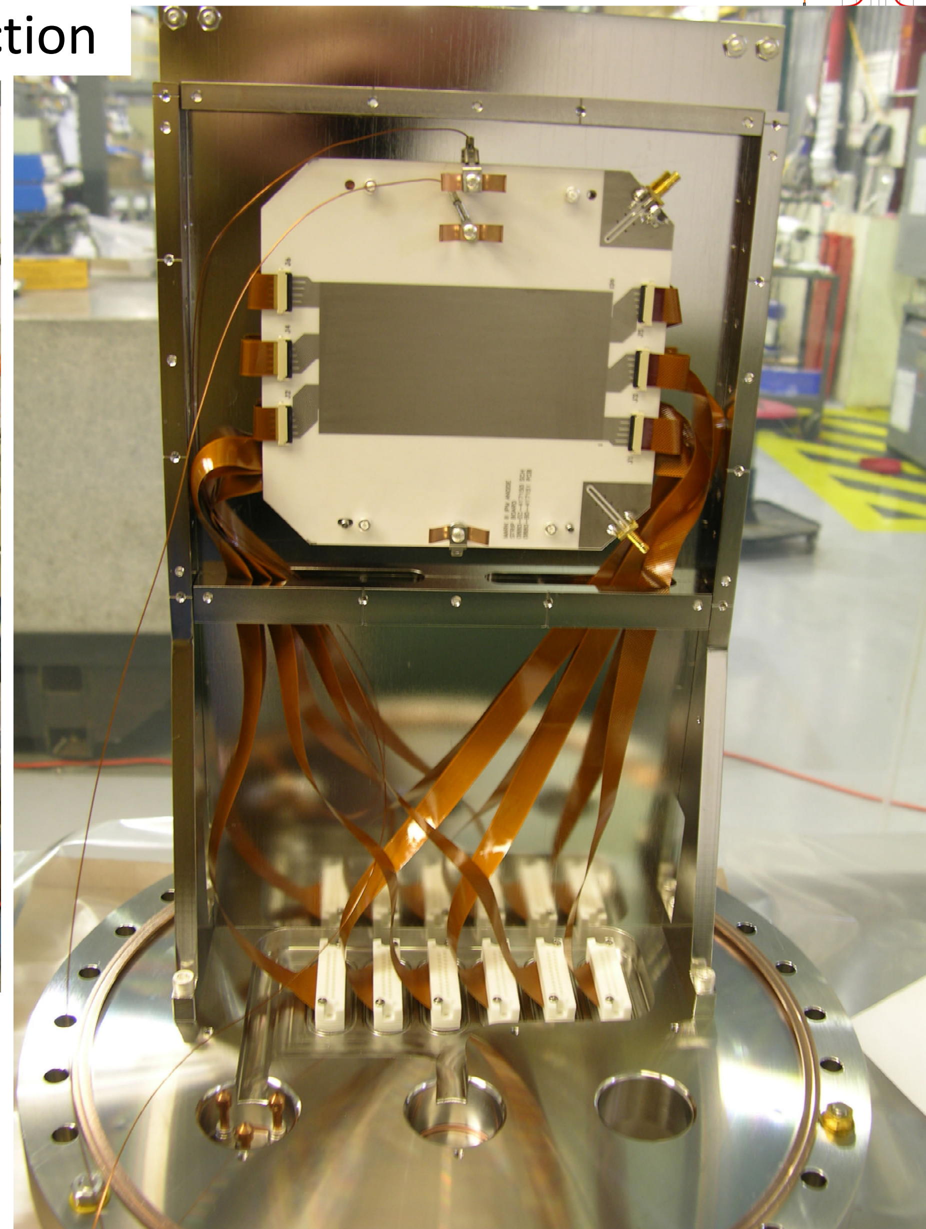
# Mark-II, and Tevatron Internals

Tray design for quick extraction for MCP replacement, assures accurate realignment.

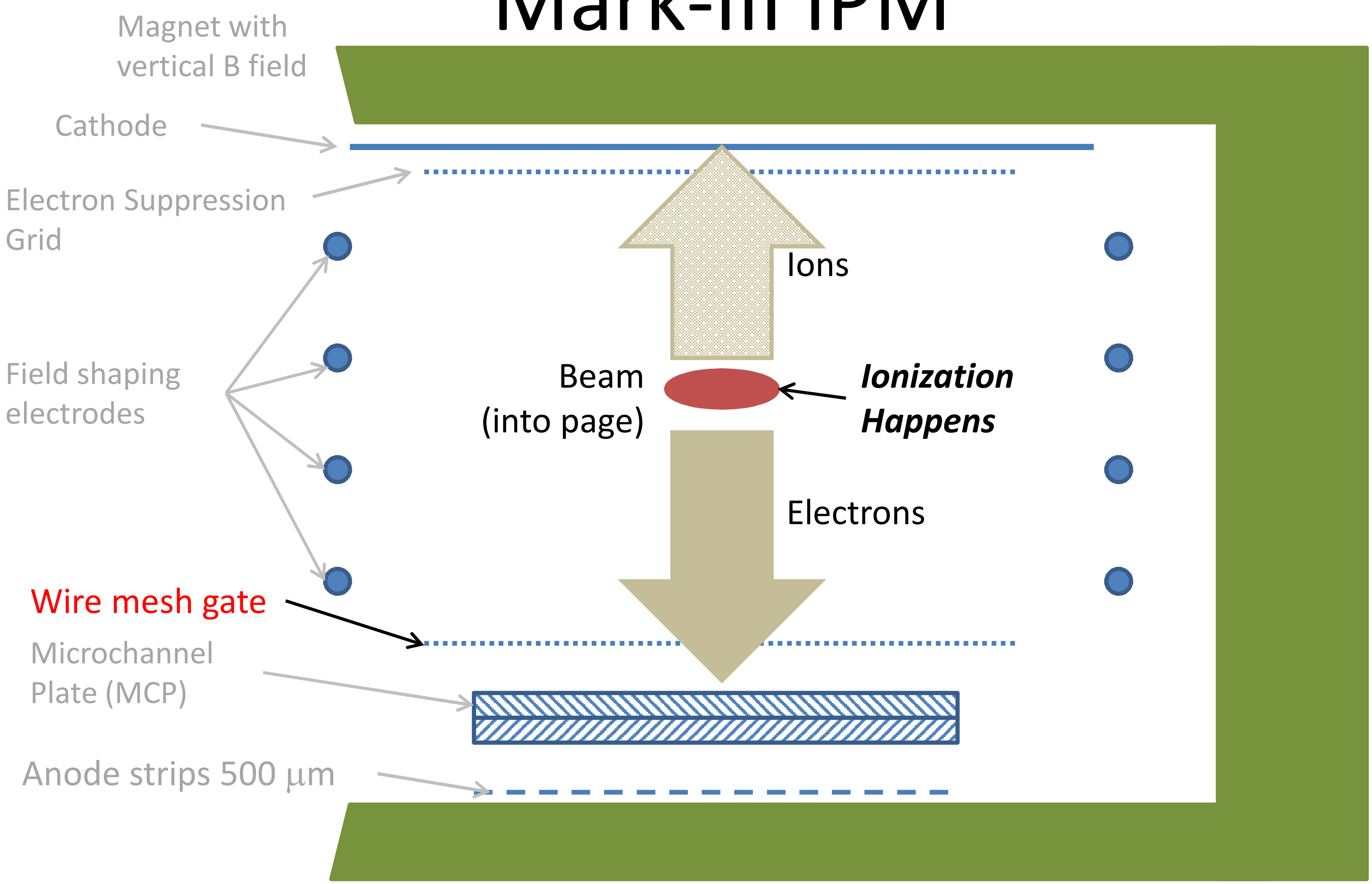


# Mark-III Internals Under Construction

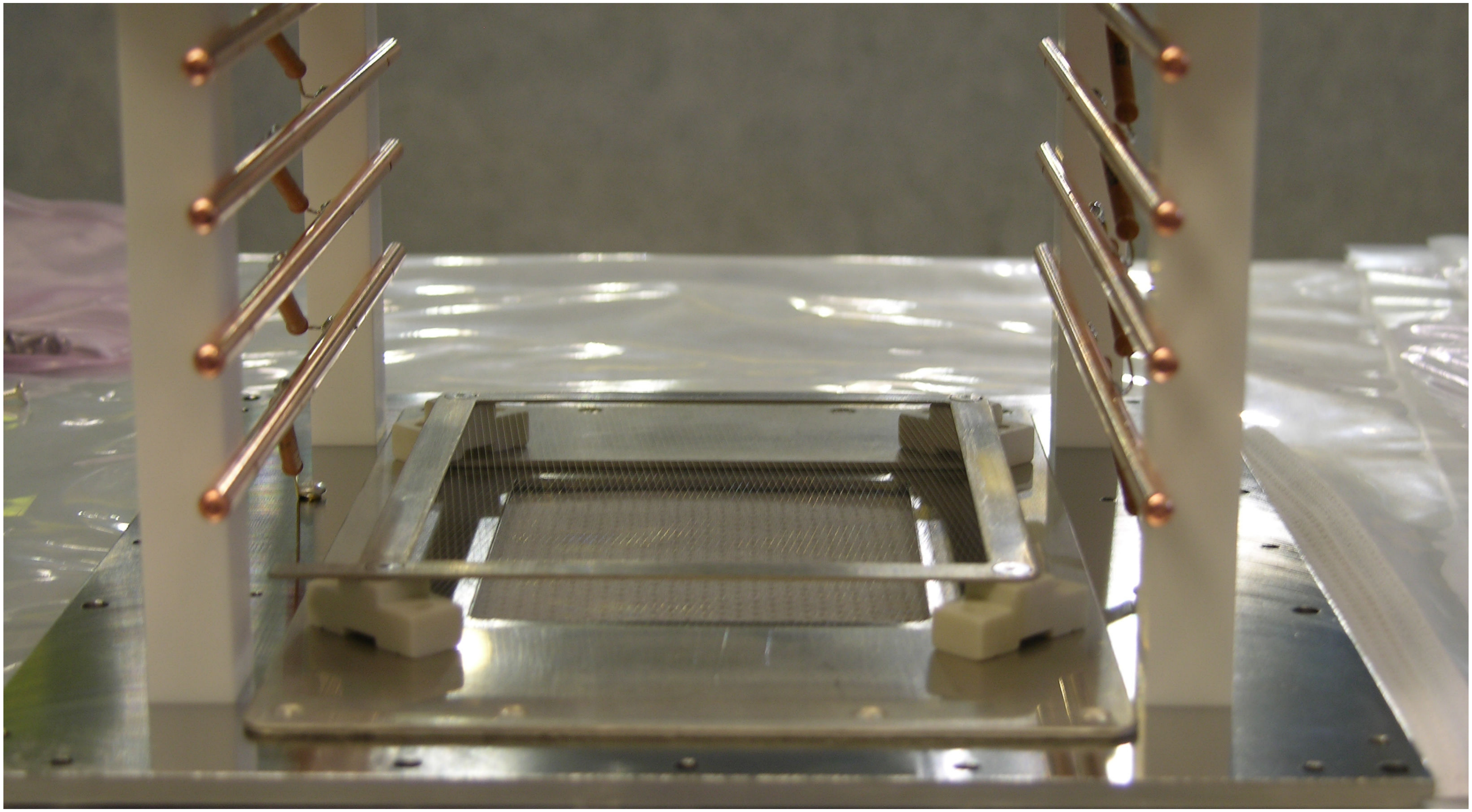




# Mark-III IPM


Magnet with vertical B field
Cathode
Electron Suppression Grid
Field shaping electrodes
Wire mesh gate
Microchannel Plate (MCP)
Anode strips 500 μm
Ions
Beam (into page)
*Ionization Happens*
Electrons

# Mark-III Control Grid

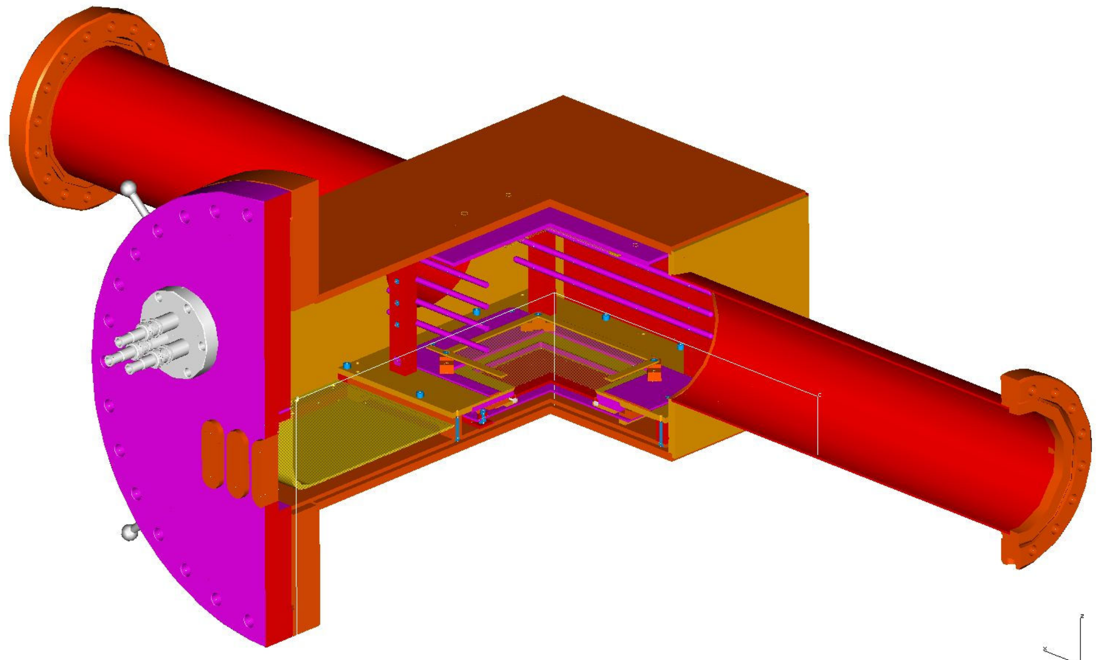


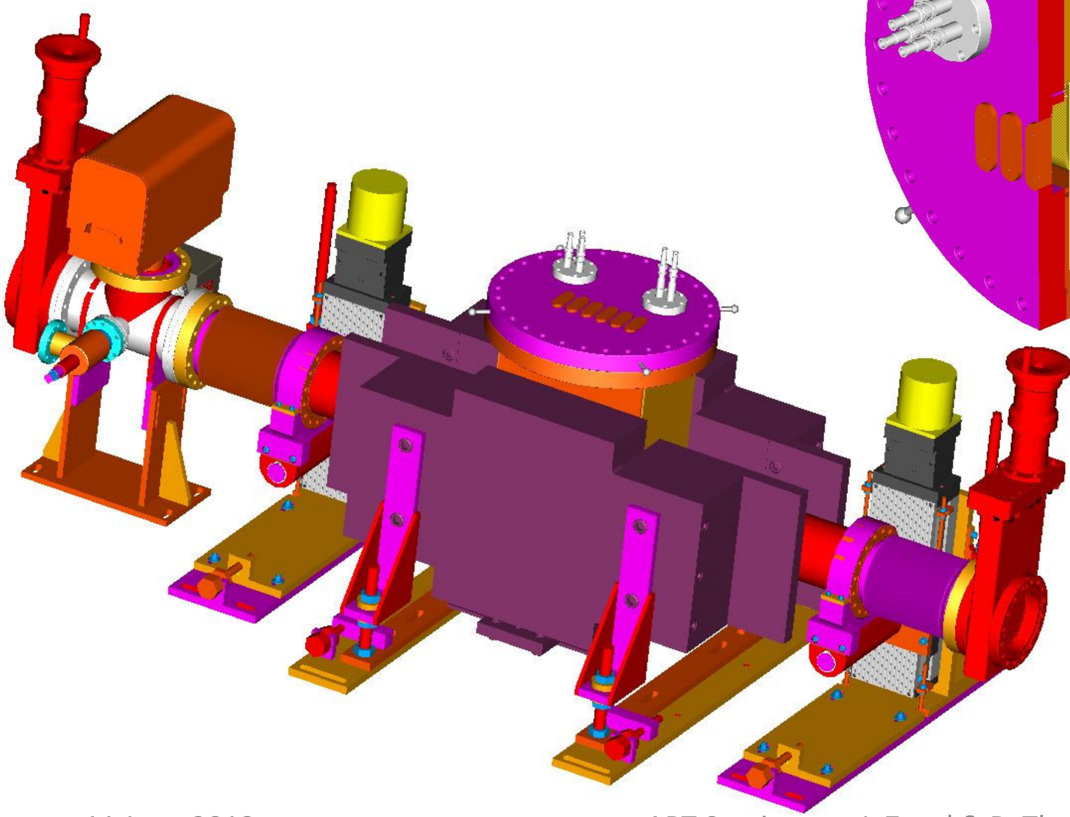
# Anode Strip Board

- Ceramic with mass terminated connectors.
  - 80% copper, 20% space.
- Booster
  - Beam sigma 4.5 mm
  - 60 Strips at 1.5 mm
  - 1.2E12 to 4.5E12 protons
- Main Injector/Recycler
  - Beam sigma 4.5 - 1.5 mm
  - 120 Strips, pitch 0.5 mm
  - MI up to 6 booster batches
  - RR slip stack up to 12 batches
  - RR max intensity 5E13
- Tevatron
  - Beam sigma 1.5 mm
  - 128 strips, pitch 0.25 mm

# Mark-III Model

Vacuum Vessel with Instrument
Now being assembled for installation.





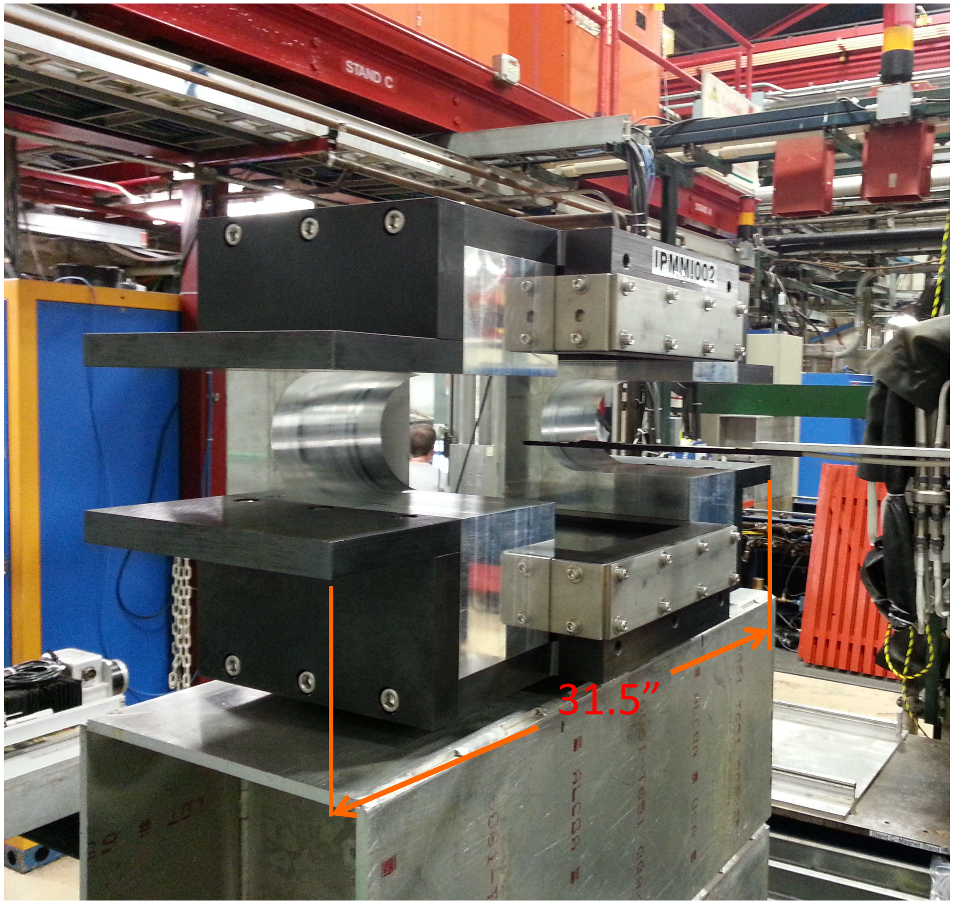
- Typical vertical installation.
- Same magnet and internals for both horizontal and vertical.
- The vacuum vessel moves in the plane of the measurement, while the magnet is fixed.

Instrumentation Department

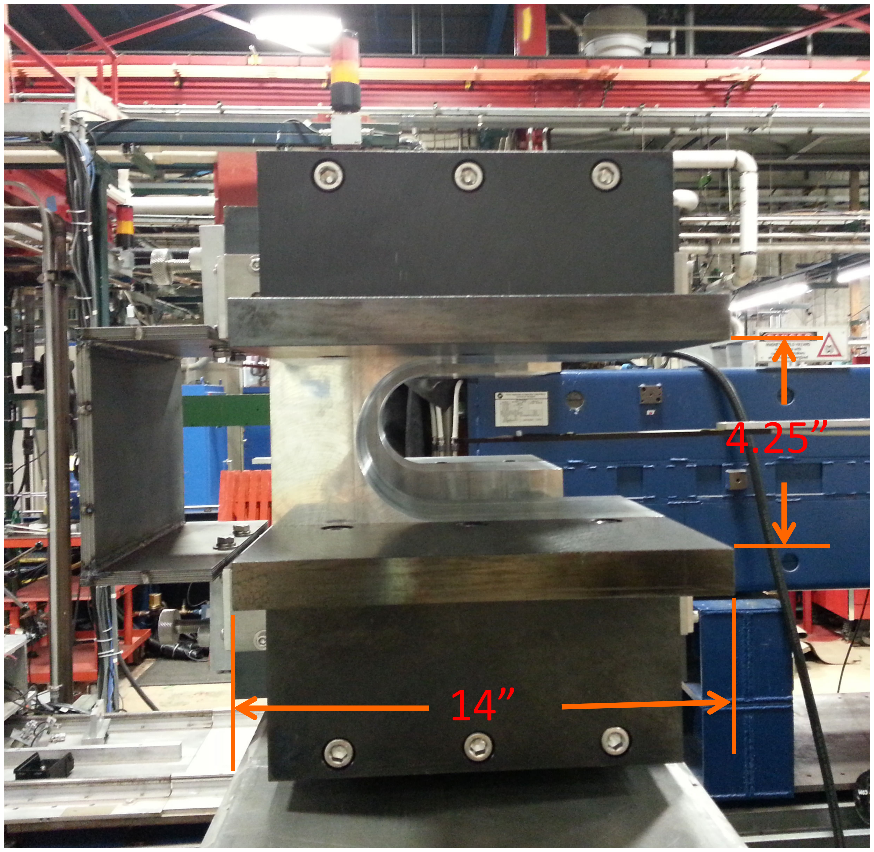
# Main Injector Mark-III Magnet

Magnet MIIPM001 on measurement stand for integral field map.
Similar to Mark-II but smaller.
1KG center field and half correction up and downstream,
Local 3 bump shunted, so beam sees close to zero integrated field.

# MARK-III Magnet




Mounted on measurement stand
for field quality map.
Hall Probe shown.



IPM

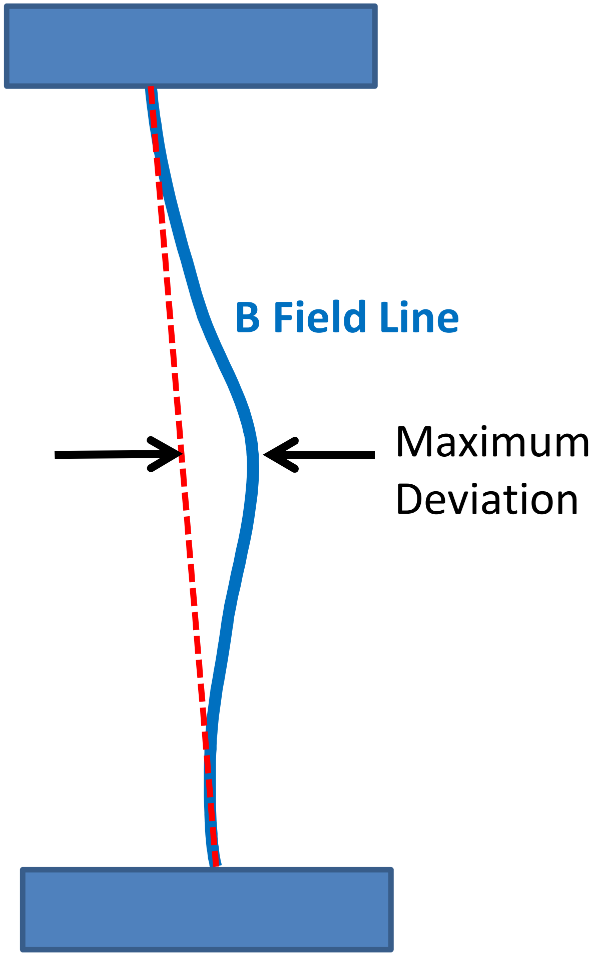
# MI Orbit Perturbation

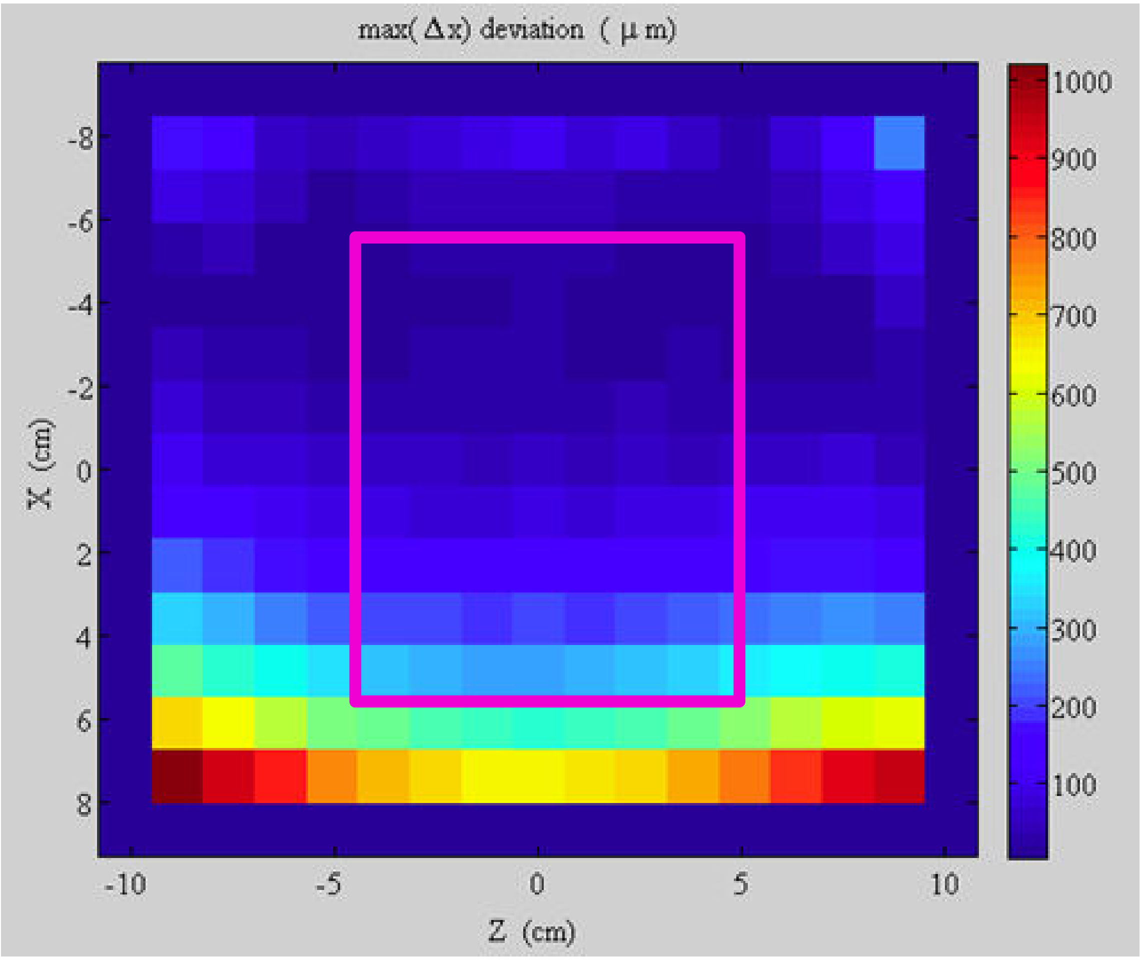
- Measured magnet integrated field is -0.001T-m
- Maximum displacement around the ring for the measured field integral is

$$D = \frac{\int B_y \, dl}{\rho_m} \frac{\beta}{2 \sin \pi \nu}$$

For the Main Injector $\rho_m \approx 27$ T-m
and the maximum β is 50, Tune, ν is 0.43,
$D \approx 0.001$ m

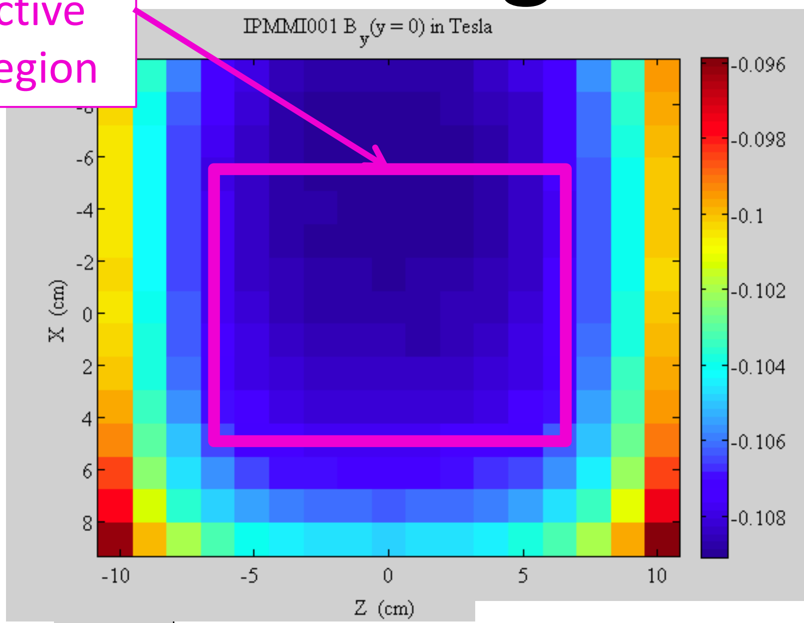
# Magnet Measurements

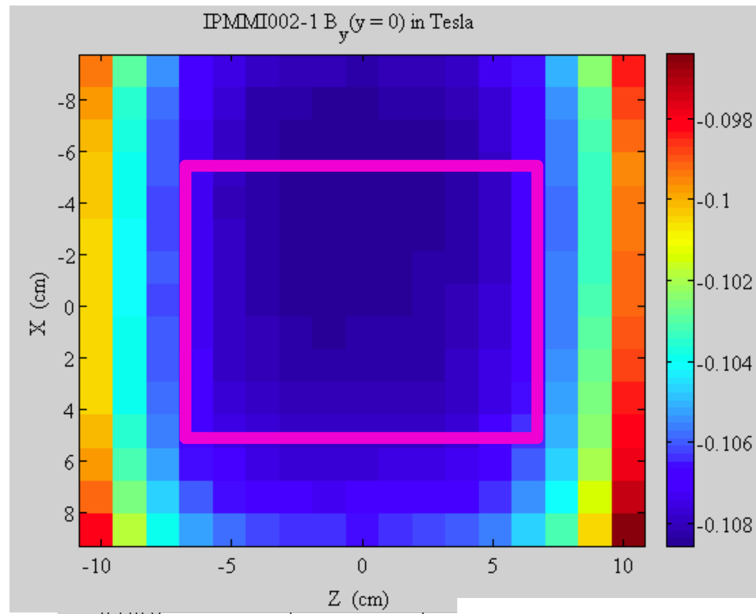


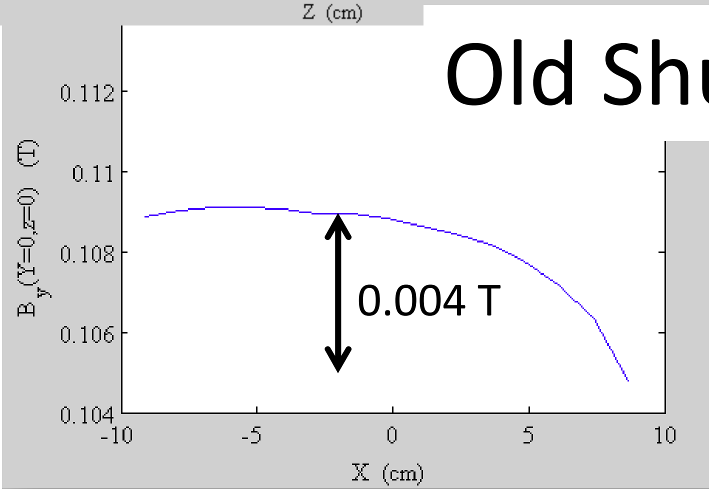
# Magnet Measurements

IPM
Active
Region

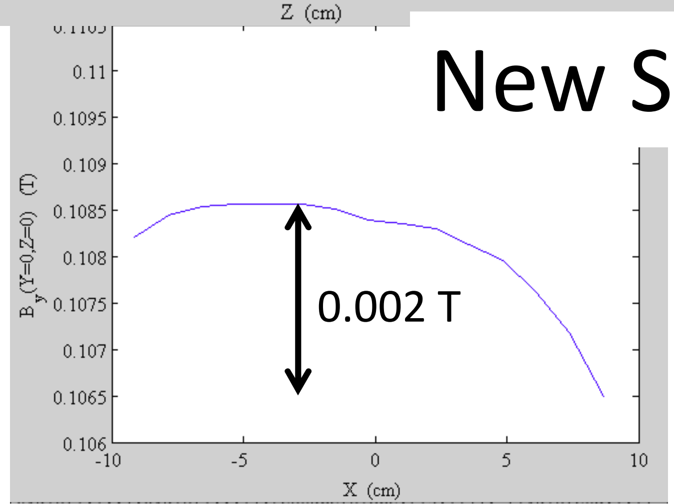


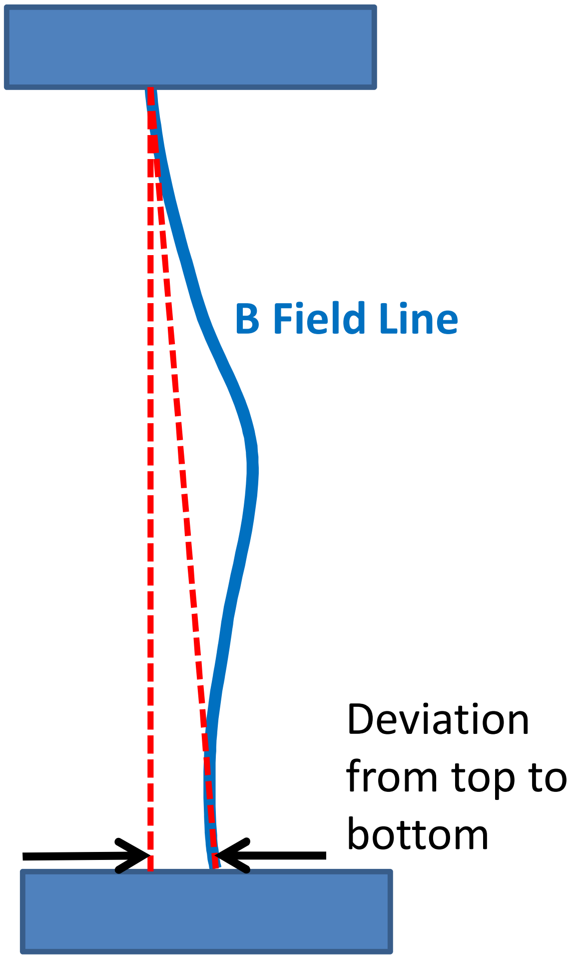

Old Shunt

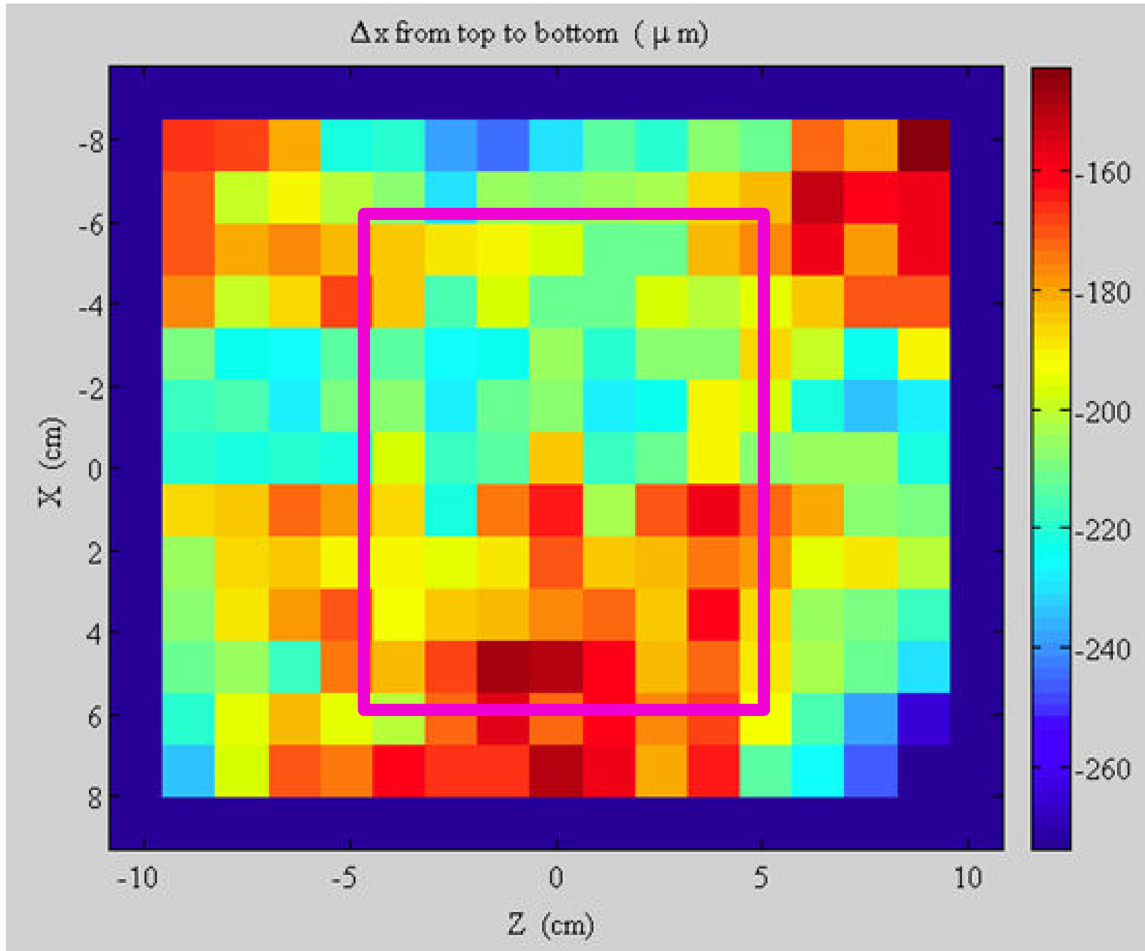



New Shunt



# Magnet Measurements




Average value of 200 μm could be hall probe rotation; corresponds to ~0.1 degrees

# Mark-III Vacuum Vessel

# IPM New Installation’s

- New Main Injector
  - Magnetic Mark-III vertical at Q103
  - Mark-II internal parts will eventually be retrofitted.
- New Recycler Magnetic Mark-III
  - Horizontal at Q104
  - Vertical at Q103
- Booster
  - Will have 2 – 30KV Electrostatic cans available

# IPM Measurement Capability

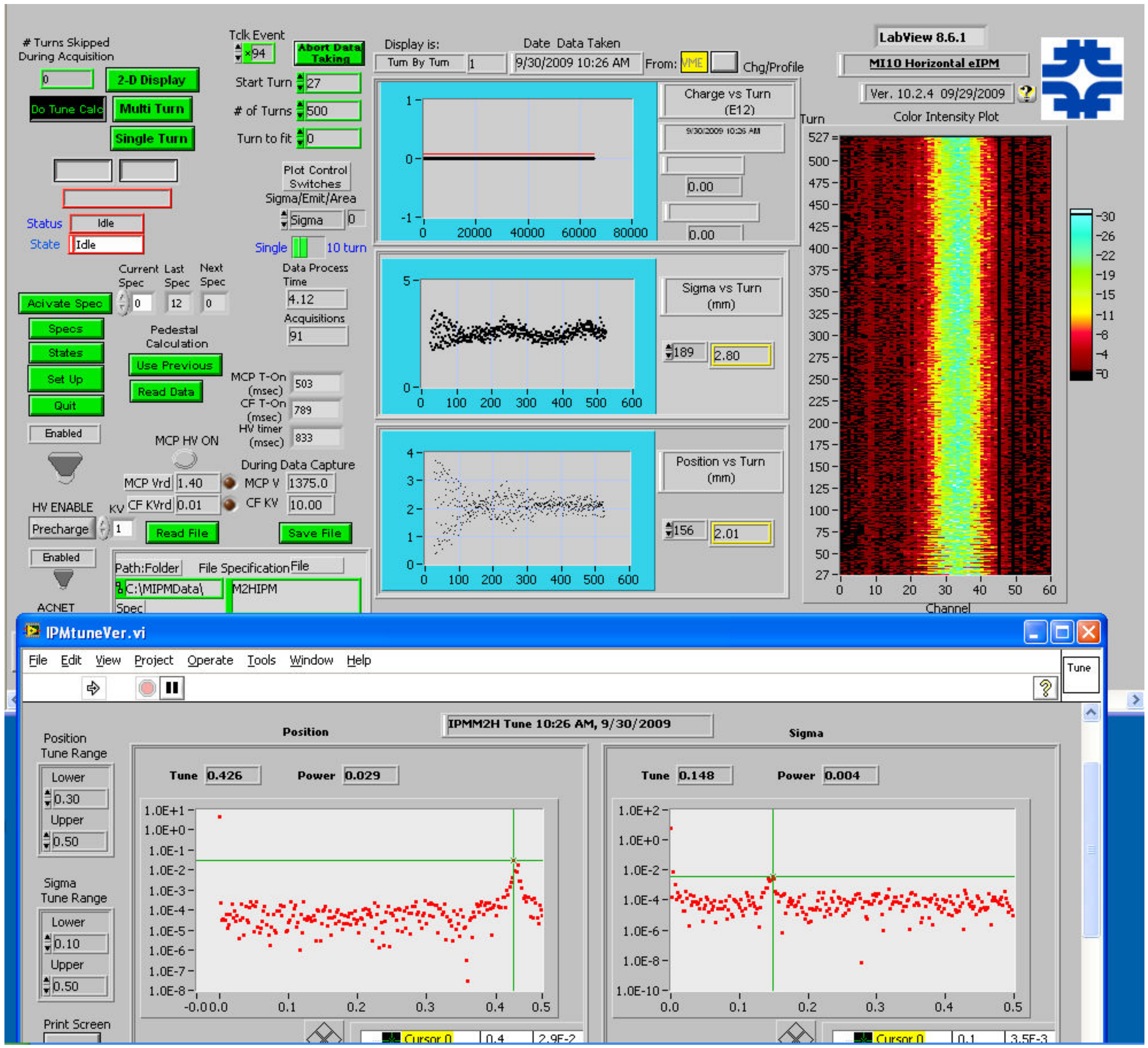
- All Systems
  - Turn by turn measurements.
    - Turns could be averaged for any accuracy desired.
  - Used for injection tuning/matching.
    - Routinely used for first 500 turns to see injection oscillations.
    - Sigma measurements anywhere in the cycle.
  - Collected 65K samples @ 1 per revolution
    - Booster 19900 turns for a full cycle.

# IPM Measurement New Features

- New Main Injector
  - Higher speed 16 channel digitizers 80MHz
    - multiple sample each batch for better accuracy/sample
    - Allows for digital filtering of signals on A/D
  - 96 Channels to be sampled using new Brian Fellenz 20 channel preamp module.
  - Control Grid to gate off electrons for unmeasured batches
    - Should significantly increase MCP life time.
  - 2000 samples at either
    - 1 Batch per revolution
    - Spread across all batches for about 300 turns

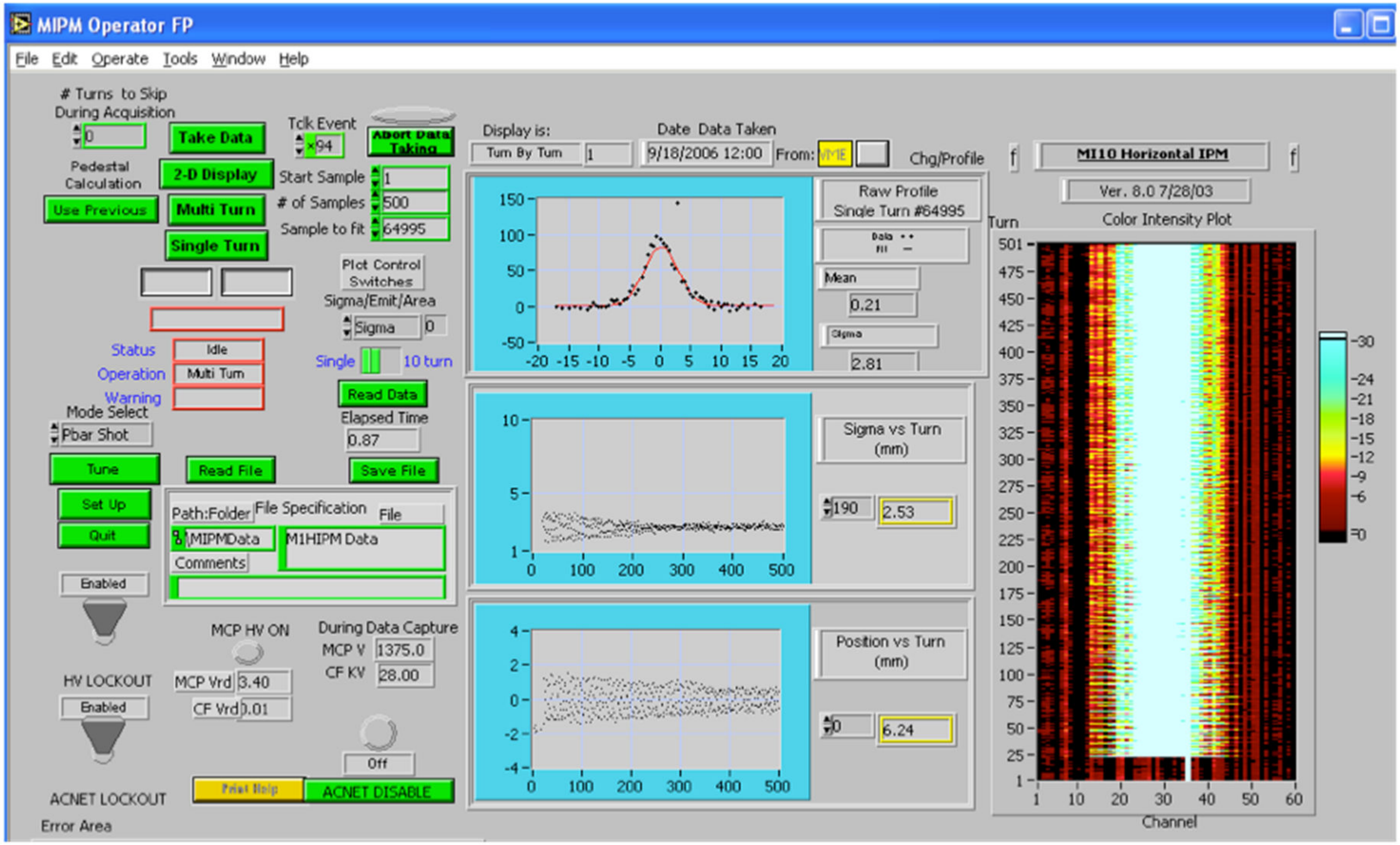
# Typical Data Display

Main Injector:
Injection tuning study.
Showing injection oscillations for the first 300 turns.



# Typical Data Display cont'd

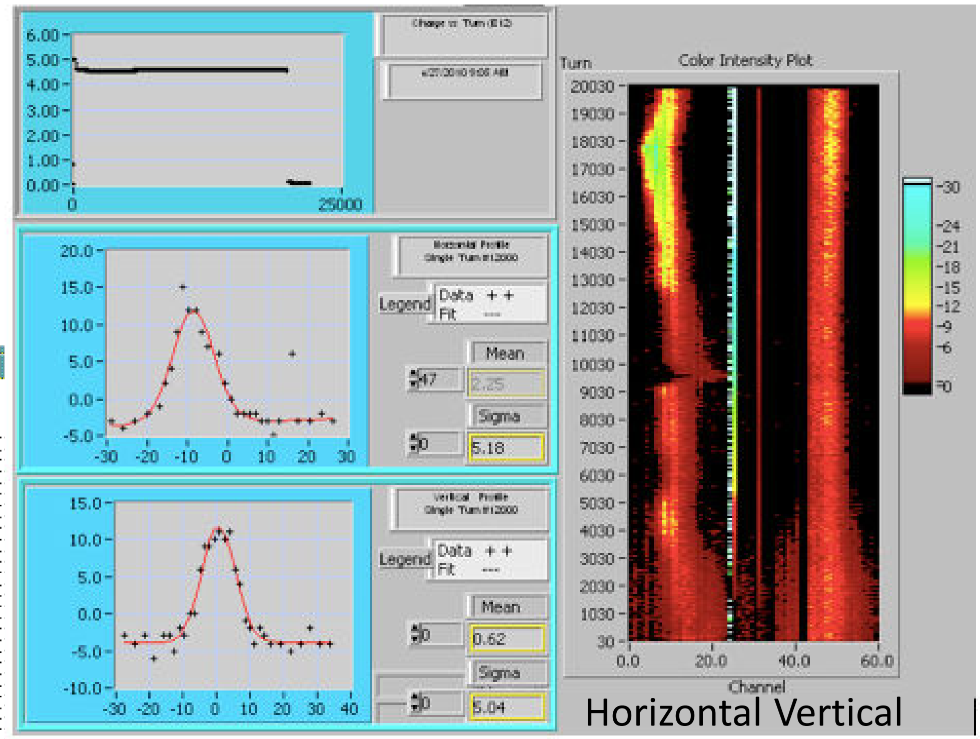
Main Injector P-Bar injection tuning.



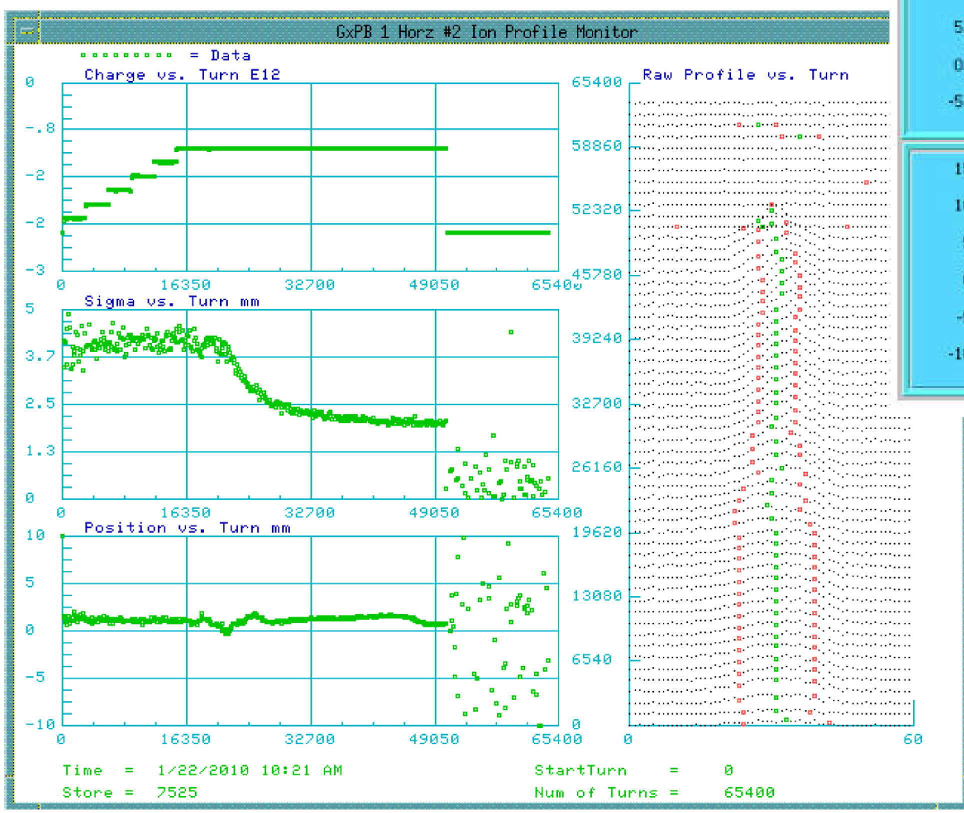
# Typical Data Display

Last

Booster LabView Front End



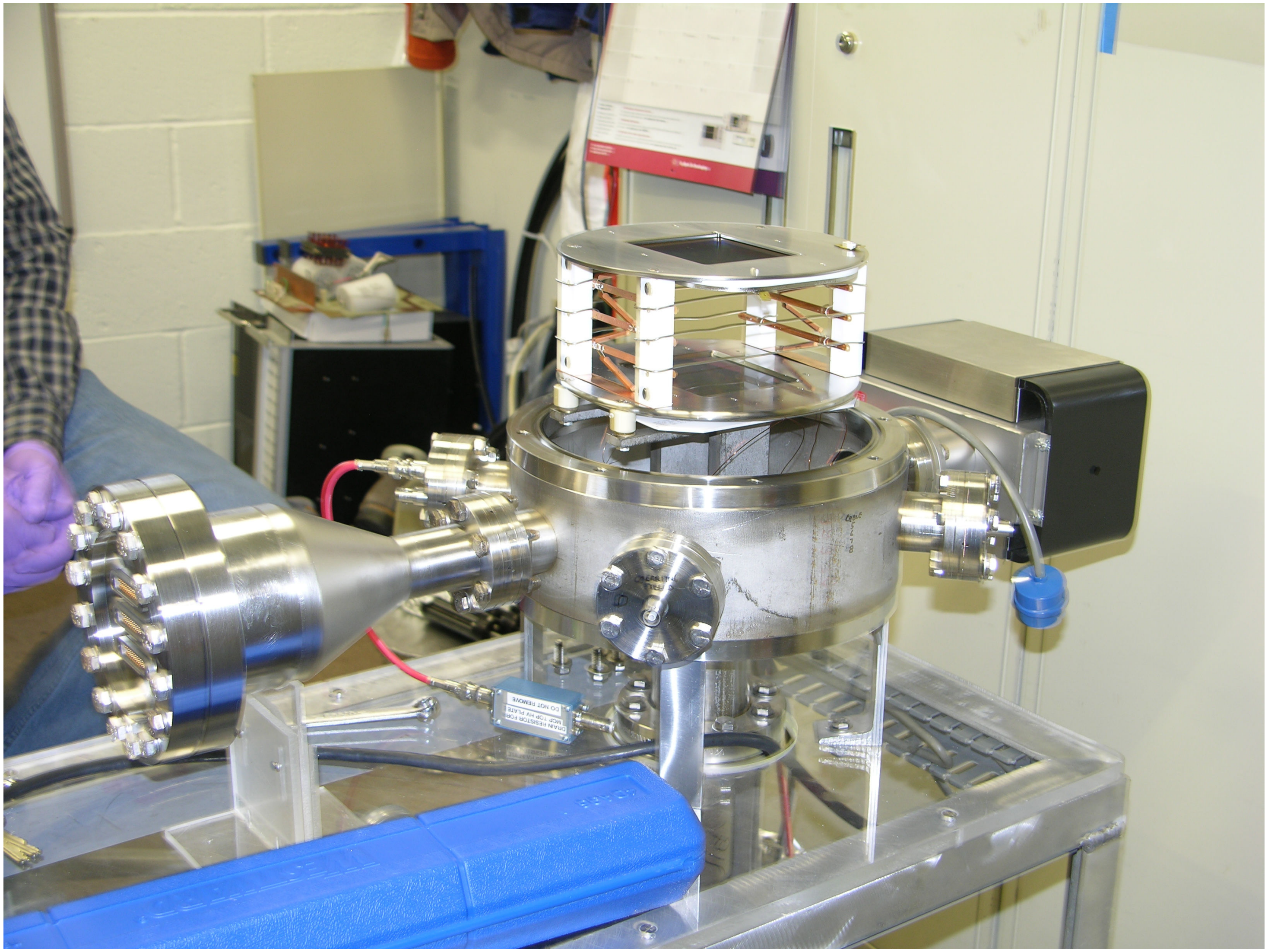

Main Injector Console Application



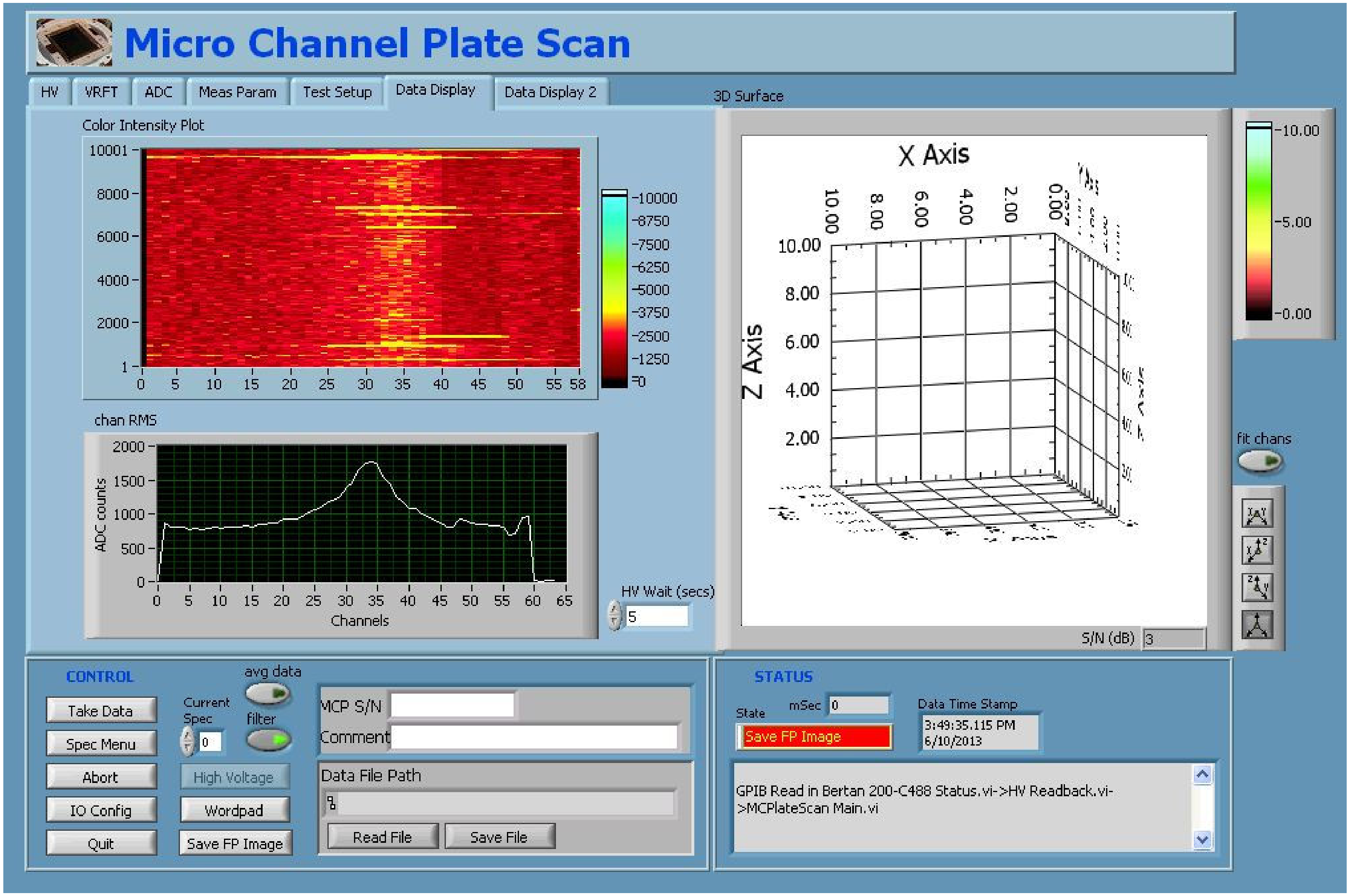

Top left trace indicates intensity.
Bottom left 2 plots –
can plot sigma and position,
or individual turn profiles.

# MCP Test Chamber

- Facility to scan MCPs for suitability and look at areas of reduced gain



# Test Chamber Measurements



# The Players

- Instrumentation
  - Dave Slimmer, Carl Lundberg, Jim Galloway, Brian Fellenz, Dan Schoo, John VanBogaert, Alexei Semenov
- Main Injector, etc…
  - Bruce Brown, Denton Morris, Jim Volk
- Mechanical Support
  - Matt Alvarez, Tom McLaughton, Dave Tinsley, Kevin Duel, Linda Valerio, Eric Pirtle, Jim Wilson, James Williams, Sali Sylejmani, Scott McCormick, Debbie Bonifas, Tom Lassiter
- Technical Division
  - David Harding, Oliver Kiemschies, Bill Robotham, Vladimir Kashikhin, Bill Robotham, Michael A. Tartaglia, Mark D Thompson, Gueorgui Velev, Dana Walbridge

# Intermission

# Gated IPM Concept

- Problem with MCP is short lifetime
  - Plate is using up lifetime whenever beam is in the machine and the IPM voltage is on
  - Voltage takes a while to raise and lower
- Would like to be able to gate the charge to preserve the MCP
  - Stop the electrons and ions from reaching the MCP
  - Allow the electrons and ions an escape path from the IPM active region
    - i.e. no Penning traps

# Gated IPM Concept

- The force on a charged particle is
  $$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) = m\frac{d\vec{v}}{dt}$$
- Assume that $\vec{E} = E_0\hat{x}$ and $\vec{B} = B_0\hat{y}$
- The solution to this is circular motion in the $\hat{x} - \hat{z}$ plane, constant motion along $\hat{y}$ and a drift along $\vec{E} \times \vec{B}$ which in this case is $\hat{z}$, i.e. along the beam
- Putting in the values for the electric and magnetic fields gives us a drift velocity of ~10 cm/μs along the proton beam direction
  - The electrons will have drifted beyond the MCP in ~1-2 μs

# MATLAB Simulation

- Simulation tracks particles through arbitrary E and B fields
- Uses interpolation to obtain the fields at any point from previously calculated field distributions
- Propagates using a relativistic formula

$$\mathbf{F}(\mathbf{r},t) = \frac{d\mathbf{p}}{dt} = m\frac{d\tilde{\gamma}\mathbf{v}}{dt} = m\left(\mathbf{v}\frac{d\tilde{\gamma}}{dt} + \tilde{\gamma}\mathbf{a}\right)$$

$$\mathbf{F}(\mathbf{r},t) = m\tilde{\gamma}\left(\mathbf{a} + \tilde{\gamma}^2\tilde{\boldsymbol{\beta}}\left(\tilde{\boldsymbol{\beta}}\cdot\mathbf{a}\right)\right)$$

Invert

$$\mathbf{a} = \frac{1}{\tilde{\gamma}m\left(1+\tilde{\gamma}^2\tilde{\beta}^2\right)}\left[\mathbf{I} + \tilde{\gamma}^2\left(\tilde{\beta}^2\mathbf{I} - \tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right)\right]\mathbf{F} = \frac{1}{\tilde{\gamma}m}\left[\mathbf{I} - \frac{\tilde{\gamma}^2}{\left(1+\tilde{\gamma}^2\tilde{\beta}^2\right)}\tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right]\mathbf{F}$$

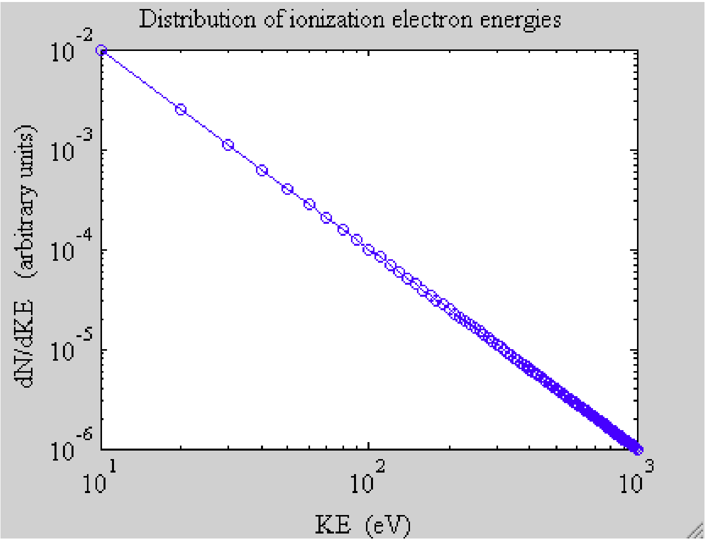
$$\mathbf{a} = \frac{1}{\tilde{\gamma}m}\left[\mathbf{I} - \tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right]\mathbf{F}$$

# Matlab Simulation

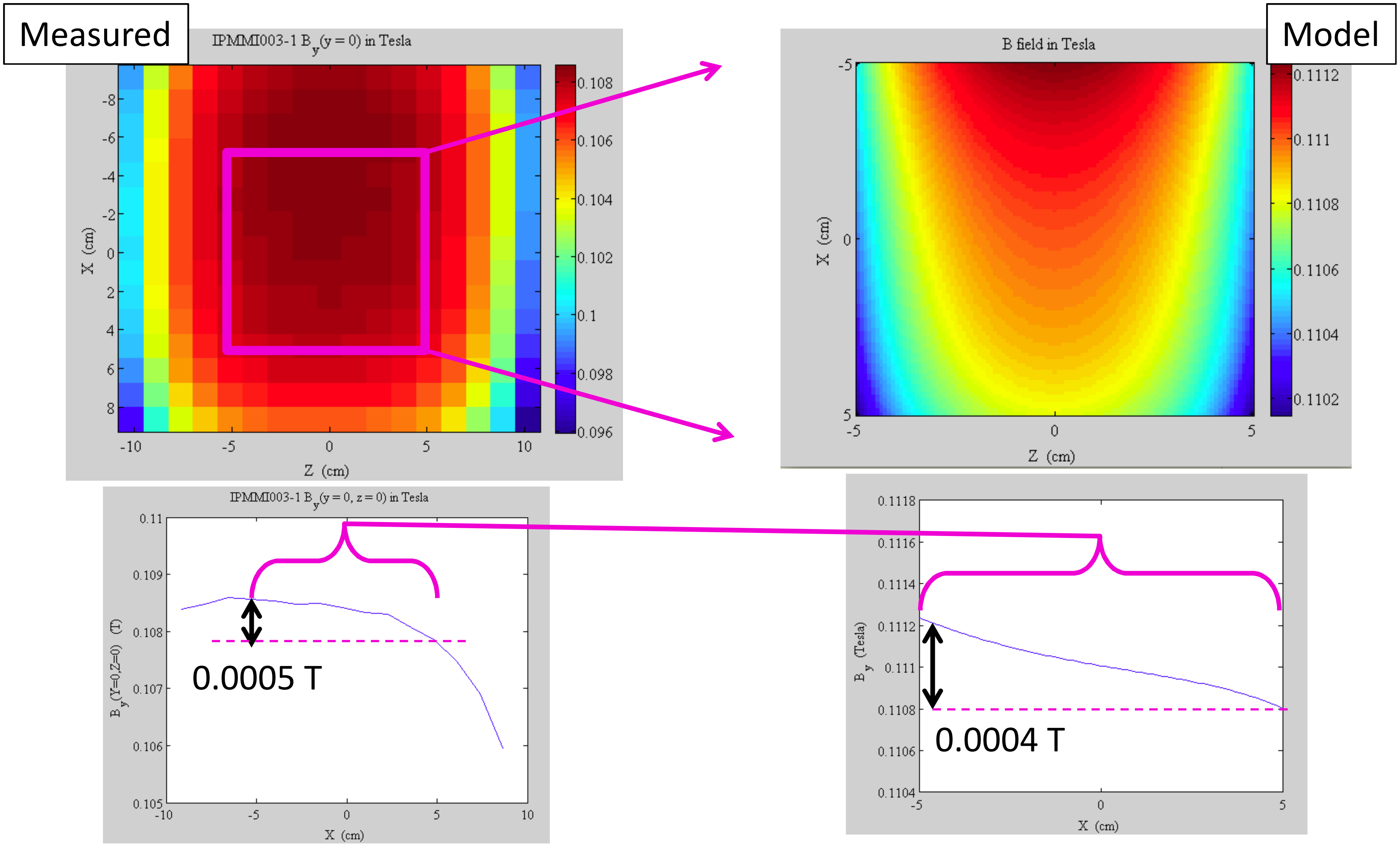
- Once the acceleration is determined, a discrete evaluation of the differential equation of motion is used to step the particles
- The magnetic and electric fields are handled separately
  - Magnetic contribution to the motion is only applied to the components perpendicular to the B field
  - Magnitude of the velocity perpendicular to the B field is forced to be preserved, since the B field does no work
    - This in particular helps with the tight spirals along the field lines

# Matlab Simulation

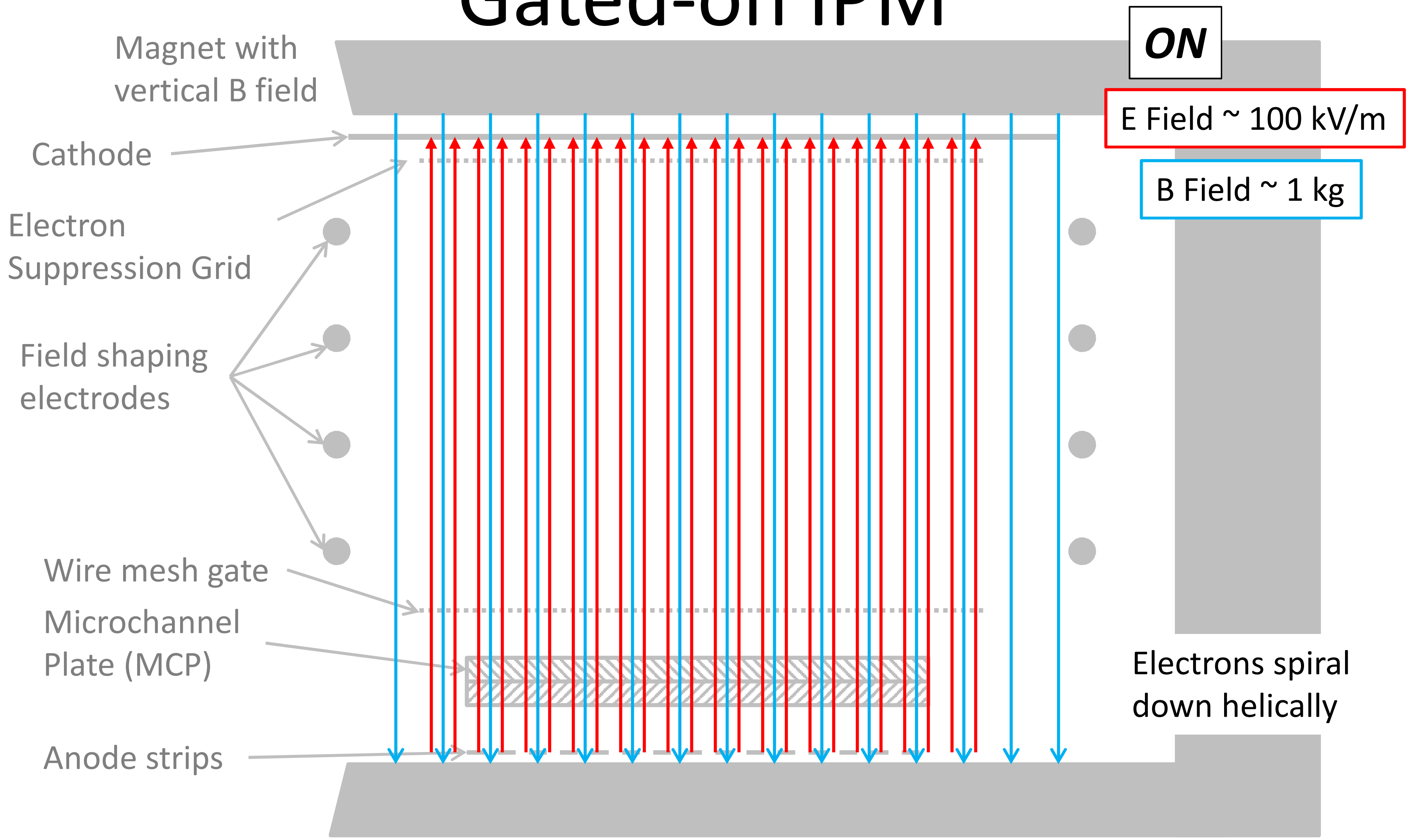
- The electric and magnetic fields of the bunch are calculated before hand for various bunch parameters
  - Shifted as a function of time to represent the moving beam
- Electric field of IPM from a 2-D Poisson calculation
- Magnetic field from 3-D magnet model
- Ionized particle distributions are random in emission angle with $1/E^2$ energy distribution

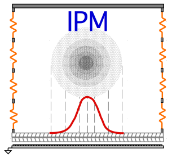


# Magnetic Field in Simulation



# Gated-on IPM

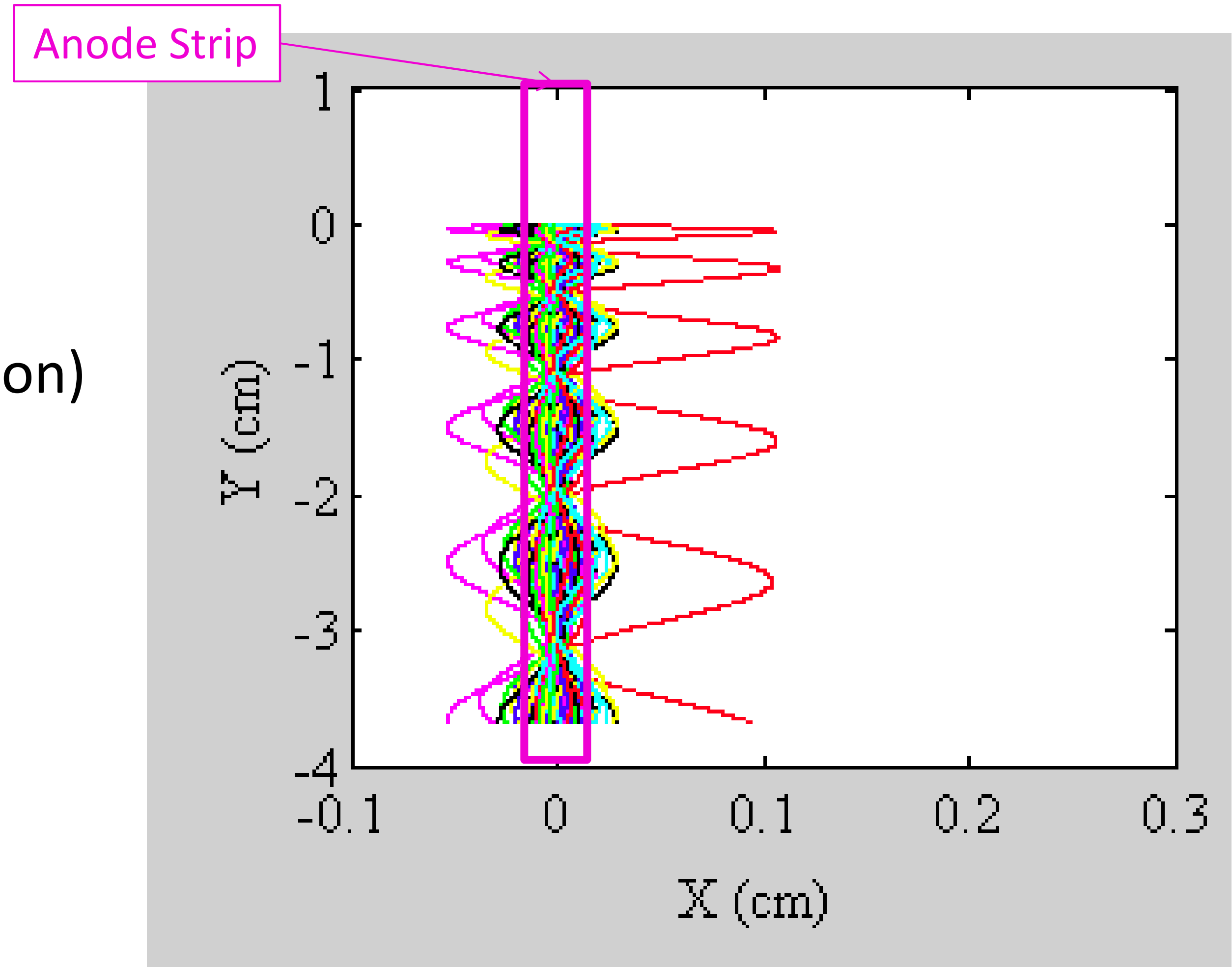

Magnet with vertical B field
Cathode
Electron Suppression Grid
Field shaping electrodes
Wire mesh gate
Microchannel Plate (MCP)
Anode strips
ON
E Field ~ 100 kV/m
B Field ~ 1 kg
Electrons spiral down helically




# Gated-on IPM

Particles originating from single point (resolution contribution)

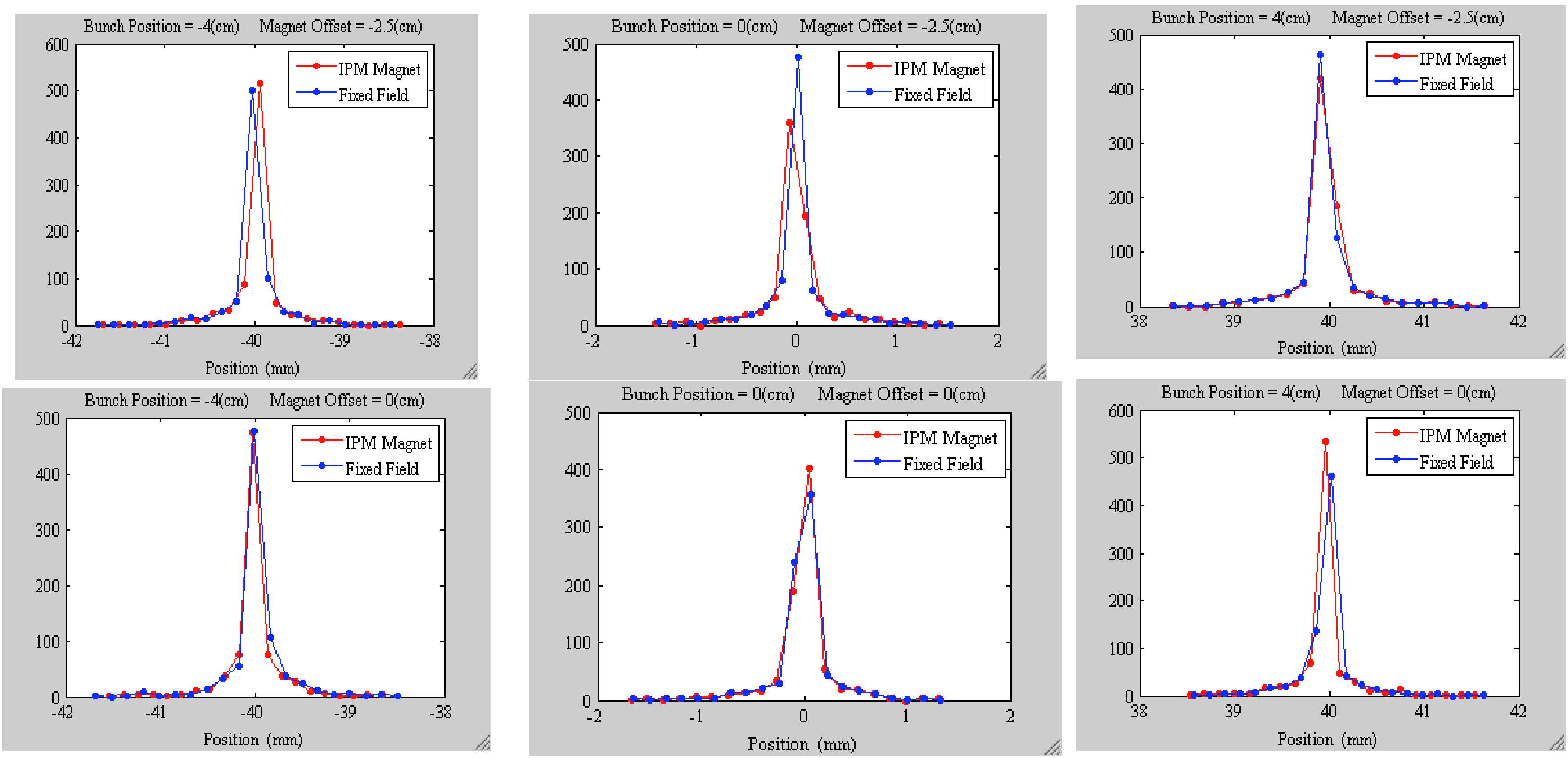
Elapsed time ~ 1.7 ns



# Gated-on IPM

Particles originating from single point
(resolution contribution)

Bunch offset refers to x



# Gated-on Expected Signal

- From figure 7 of Sauli [#], the number of primary ion pairs produced in one centimeter of a gas species *i* at one atmosphere of pressure by one minimum ionizing particle can be roughly parameterized as

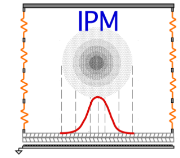
$$n_i \approx \frac{3}{2} Z_i$$

- Expressing this in terms of the proton bunch parameters and partial pressures in the beampipe one arrives at

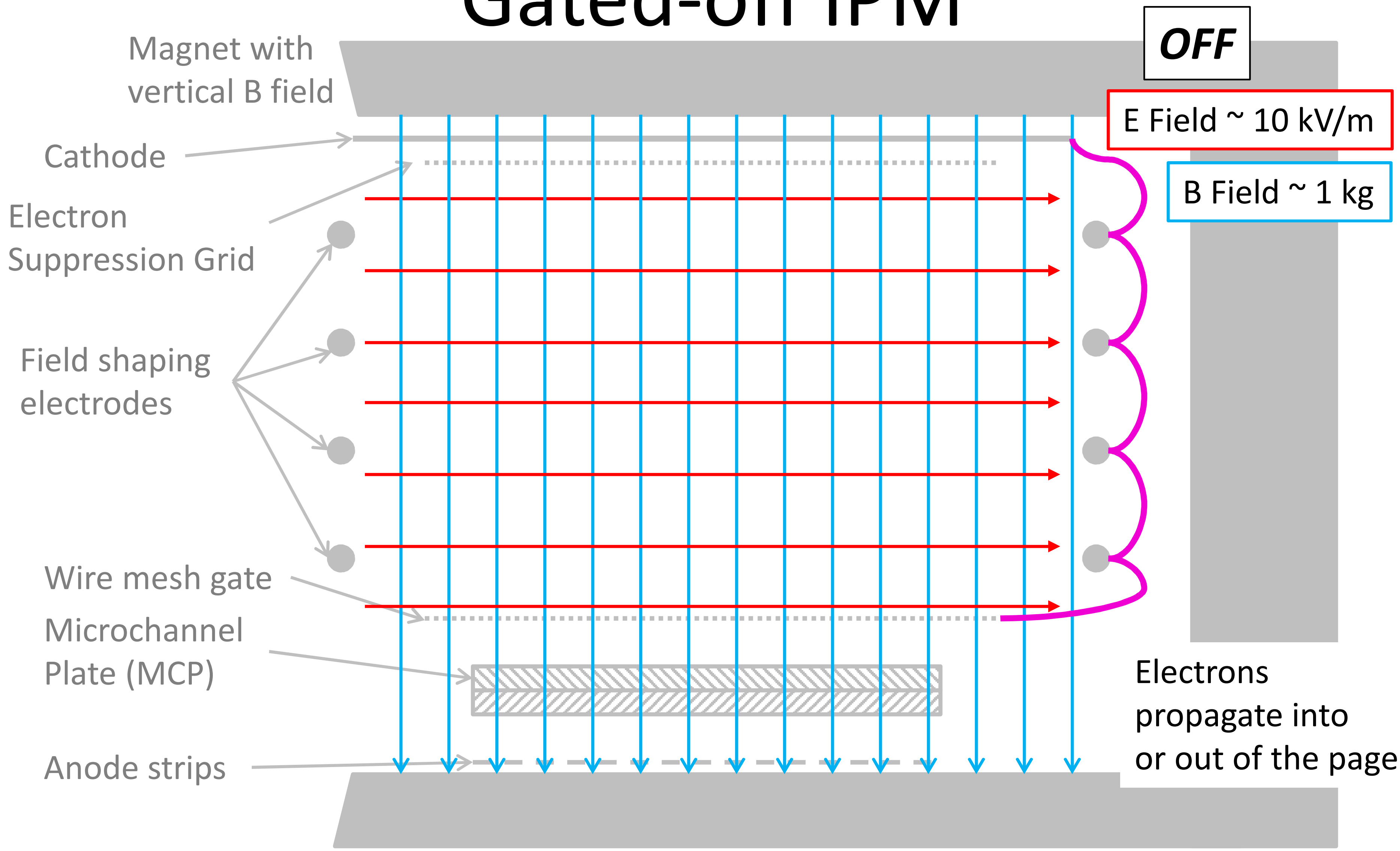
$$n_j(t) \approx \frac{QL\delta}{500 e \sigma_T \sigma_t 2\pi} \left[ e^{-\frac{(j\Delta)^2}{2\sigma_T^2}} \right] \left[ e^{-\frac{t^2}{2\sigma_t^2}} \right] \sum_i Z_i P_i$$

- At the peak of a Main Injector bunch, the number of ionization electrons is ~10 per anode strip (no MCP gain)

[#] *F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers", CERN 77-09, 3/5/77.*

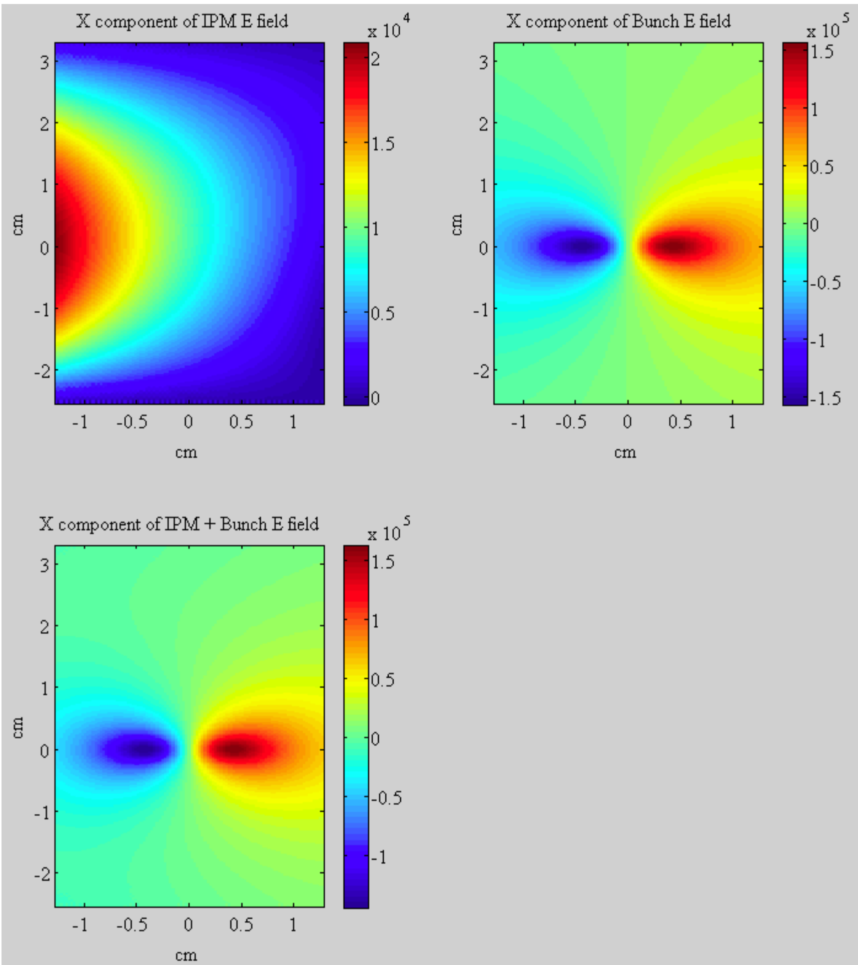



# Gated-off IPM

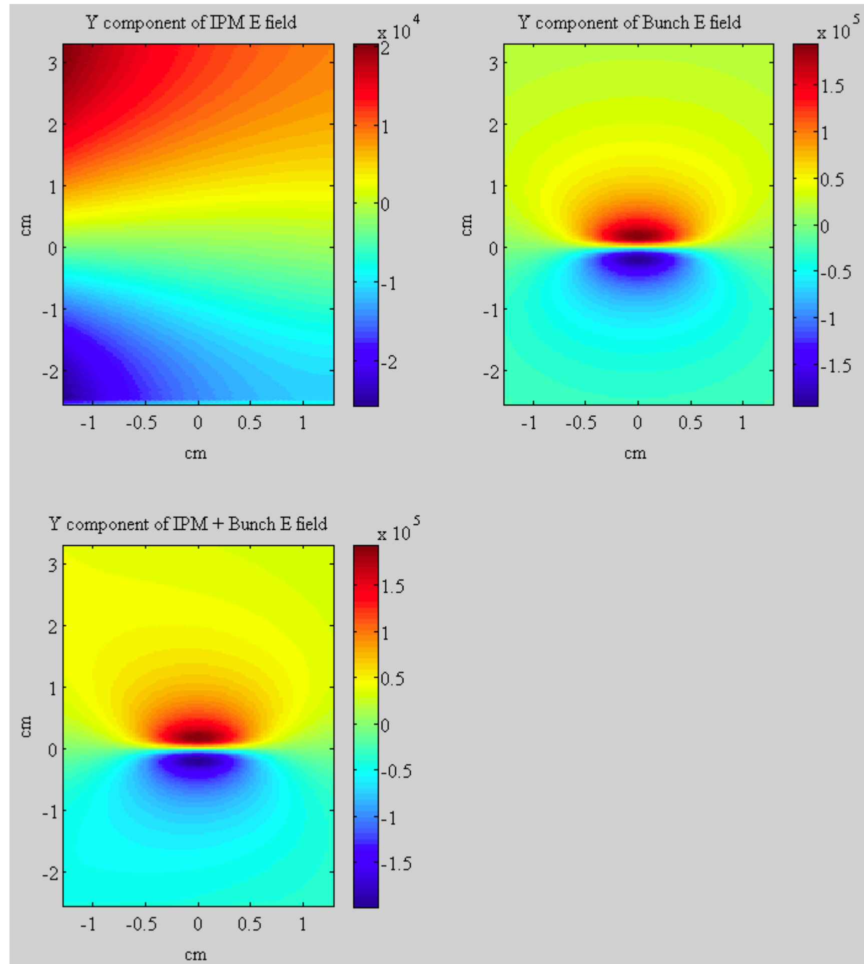


# Gated-off Fields

X Component of E field

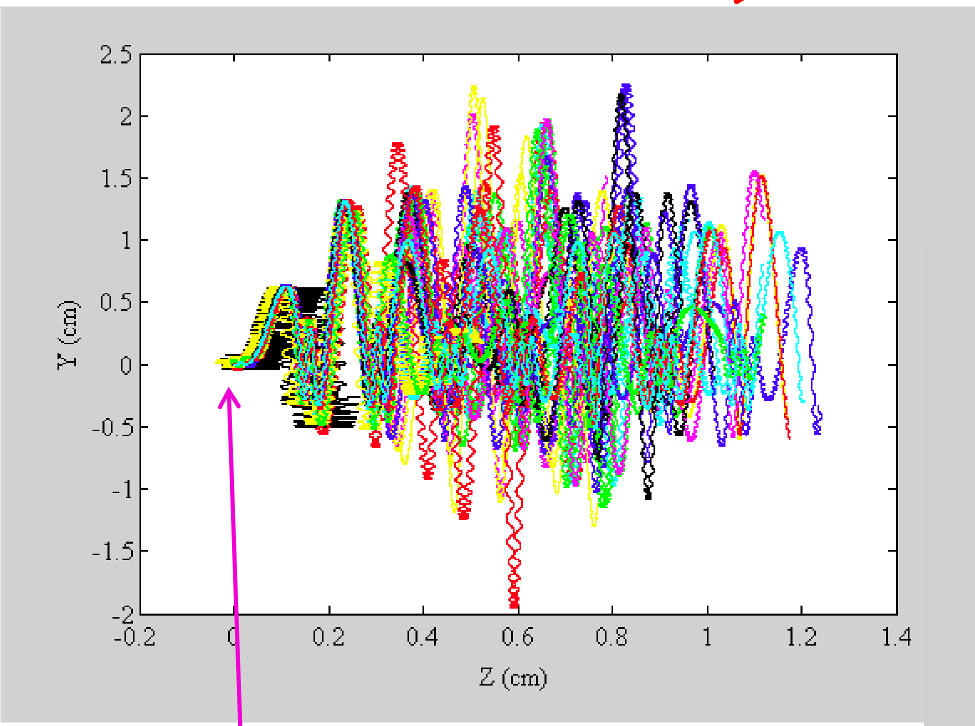



Y Component of E field



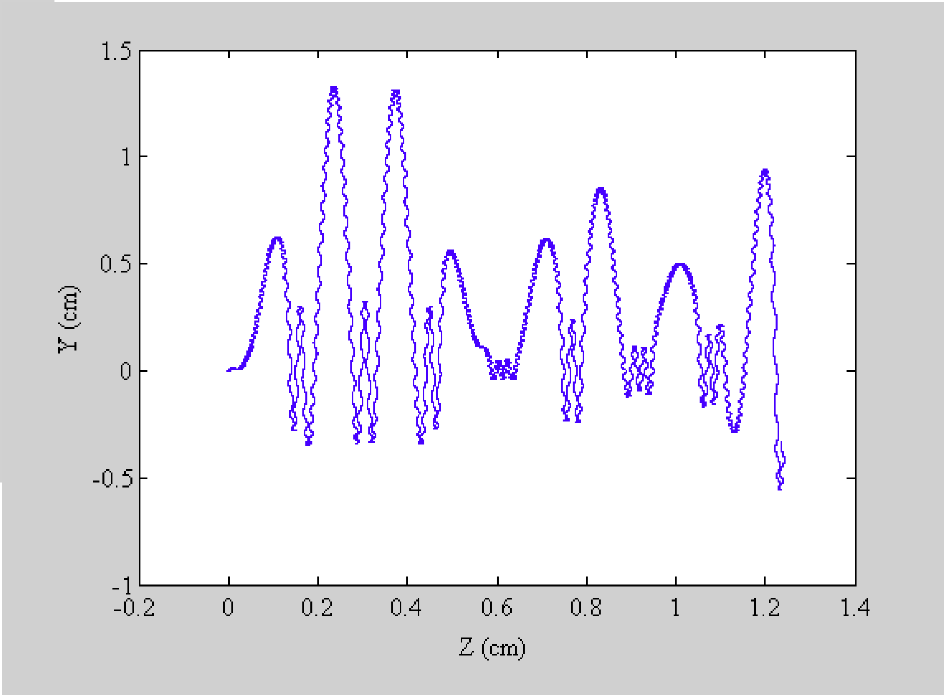
# Gated-off Motion

Electrons drift along beam direction




Particle origination point

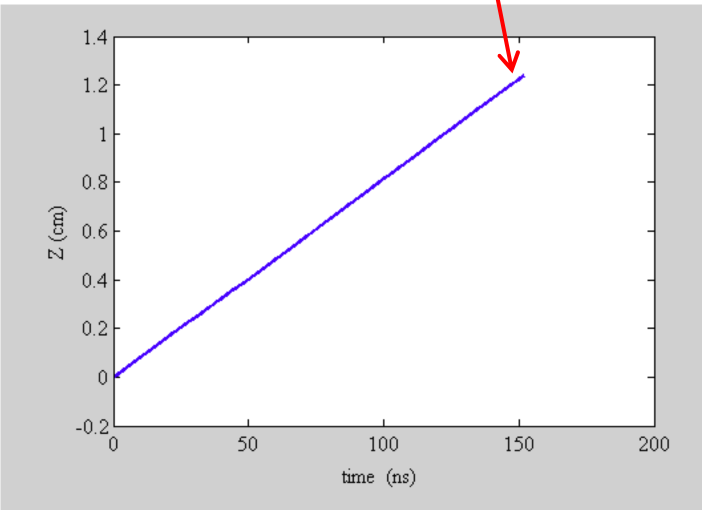
Single particle



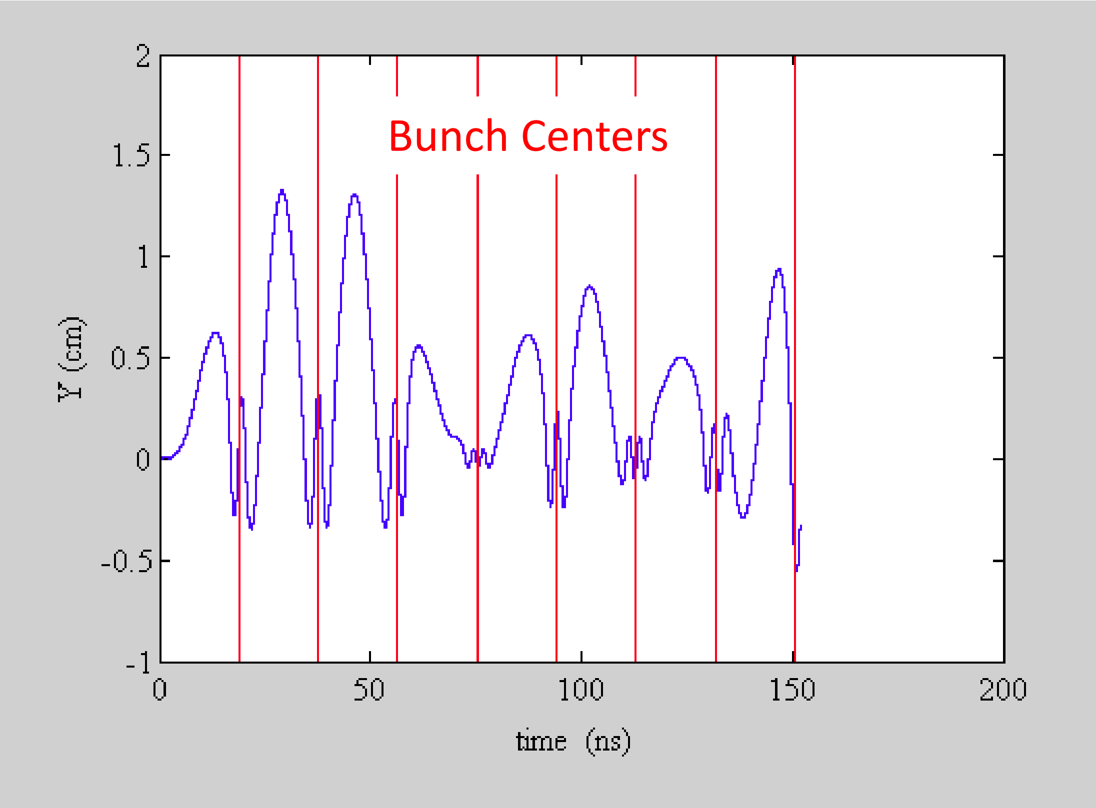
# Gated-off Behavior

*What happens when electrons reach the end of the field region?*

Drift Velocity
1.2 cm / 150 ns = 8 cm/μs
Compared to
10 cm/μs analytically estimated




Y motion vs time



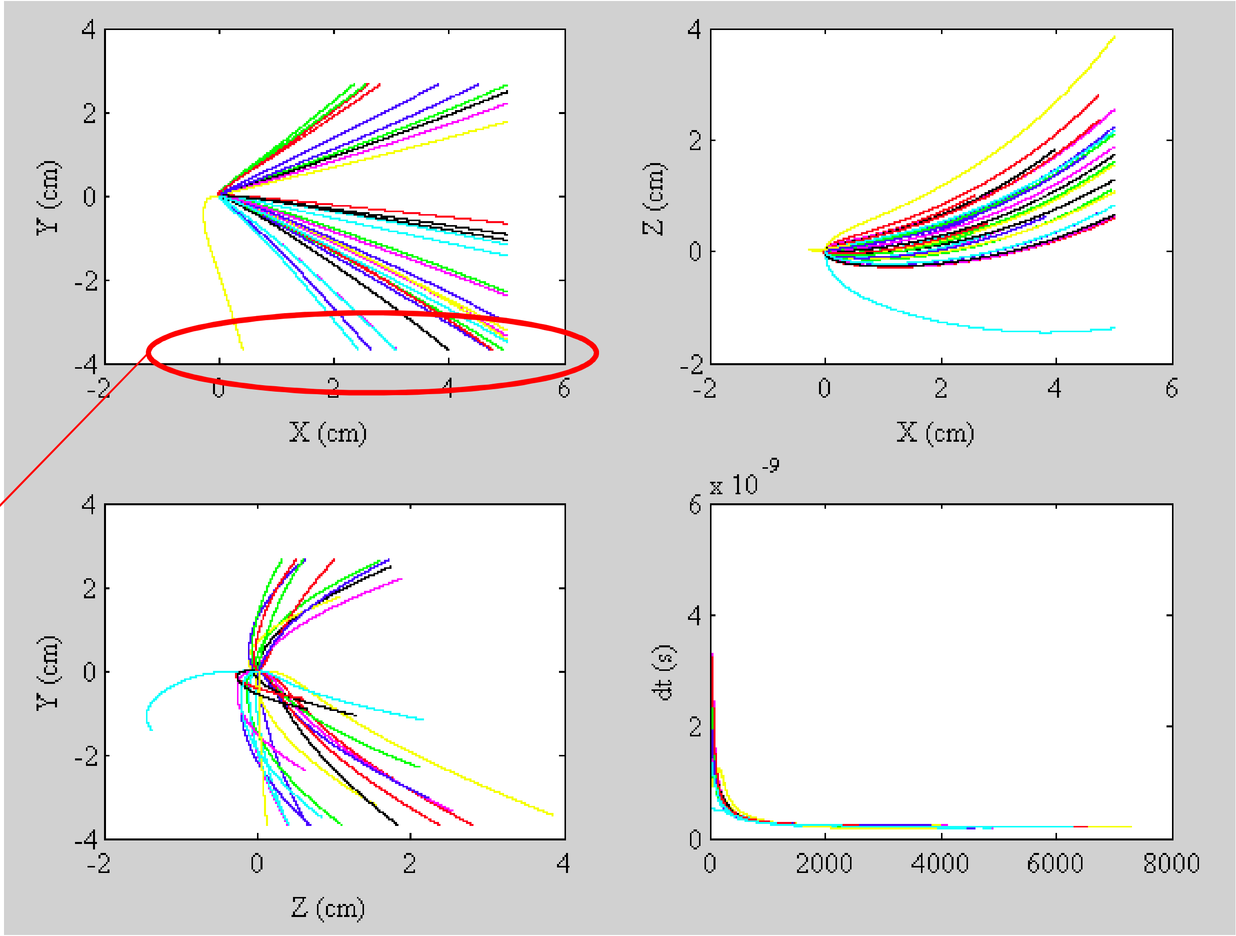
# Gated-off Ion Paths

Elapsed time is ~1.5 μs

Initially appears ok, since ions do not go much beyond the gating grid

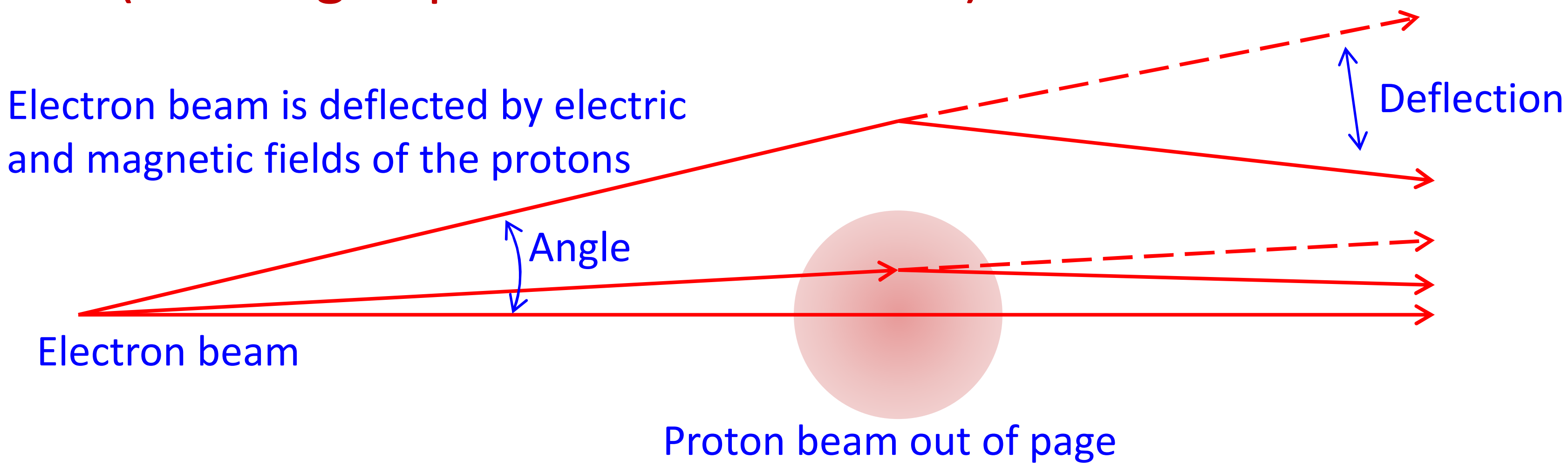
-- However --

Secondaries from ion impacts on gating grid could be a problem



# Electron Beam Profiler

- Increasing beam power in MI/RR implies the need for non-invasive instrumentation
  - Electron beam deflection technique is one choice (working implementation at SNS)




- Deflection vs. Angle provides information about the proton beam transverse profile

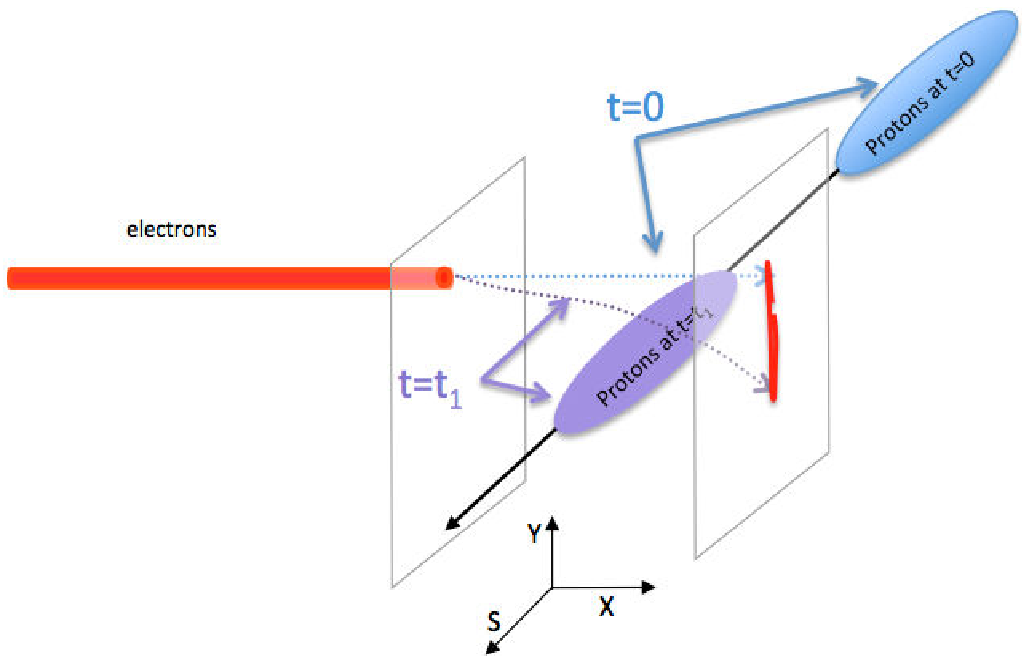
# Techniques for Main Injector

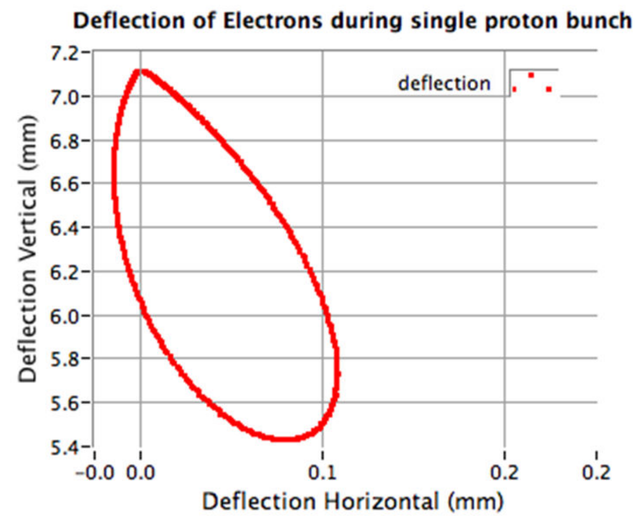
- Various techniques for measuring deflection
  - Fast scan through peak of bunch (similar to SNS)
    - Requires fast deflector (< 1 ns sweep time)
  - Slow scan, akin to flying wires (most likely solution for Nova)
    - Position the beam and record the maximum deflection as the beam passes by
      - Leave the electron beam stationary
      - Sweep the beam along the proton direction
        - » Obtain longitudinal distribution
- Collaborating with Wim Blokland at SNS who has done simulations of the various techniques

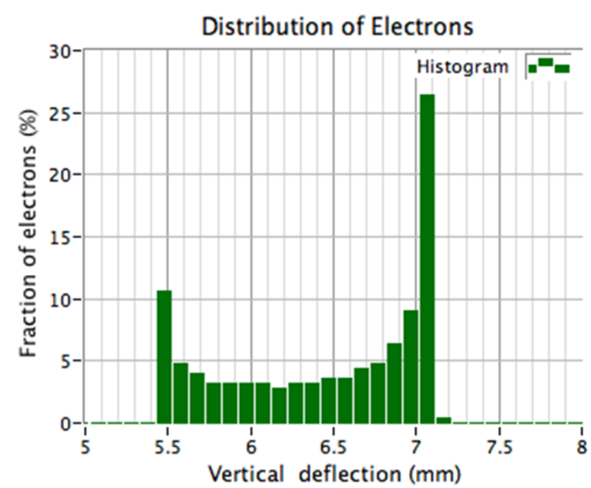
# Electron Deflection

## Slow electron sweep

- Position the electron beam
- Record the deflection of a bunch
- Move the electron beam and repeat



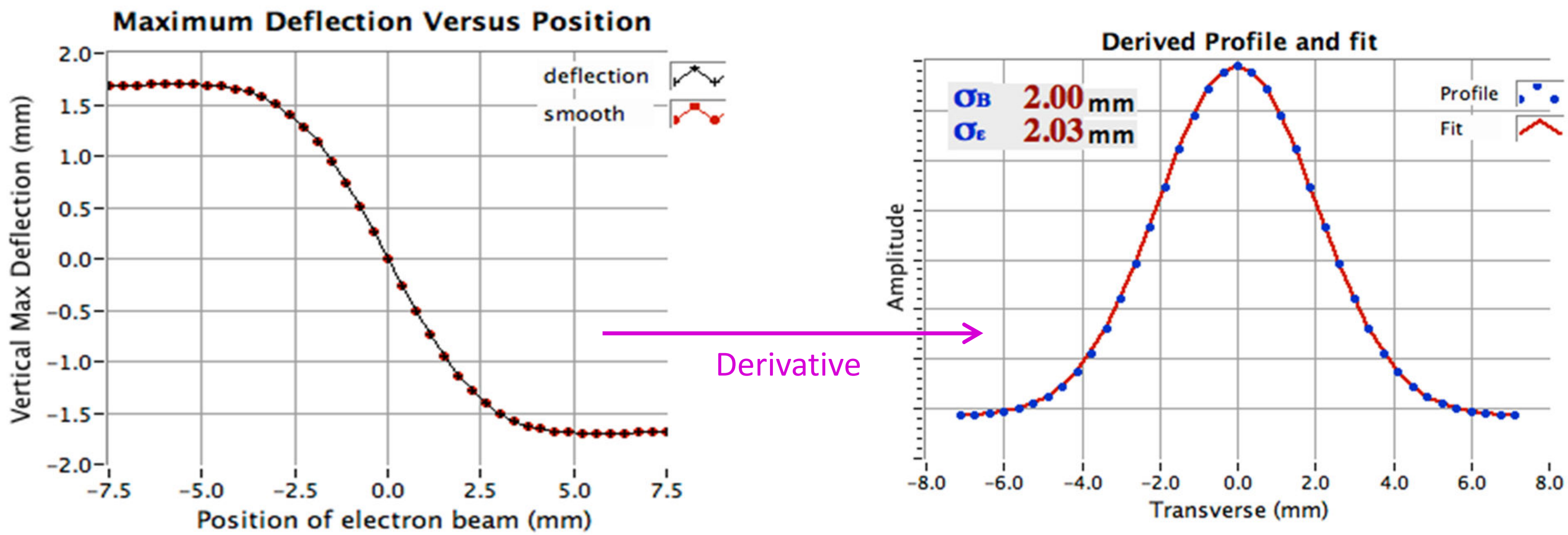




*Plots courtesy of Wim Blokland*

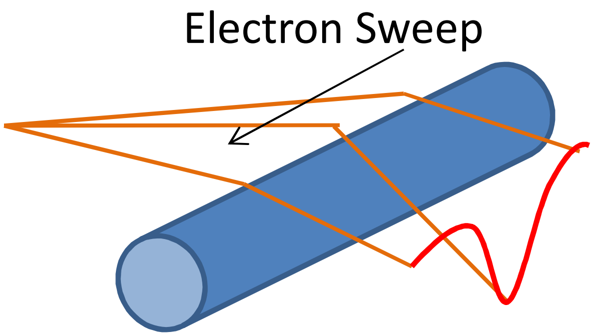
# Electron Deflection Simulation

- Step the electron beam through the proton beam and record maximum deflections
- Derivative of deflection vs. position is nominally beam profile

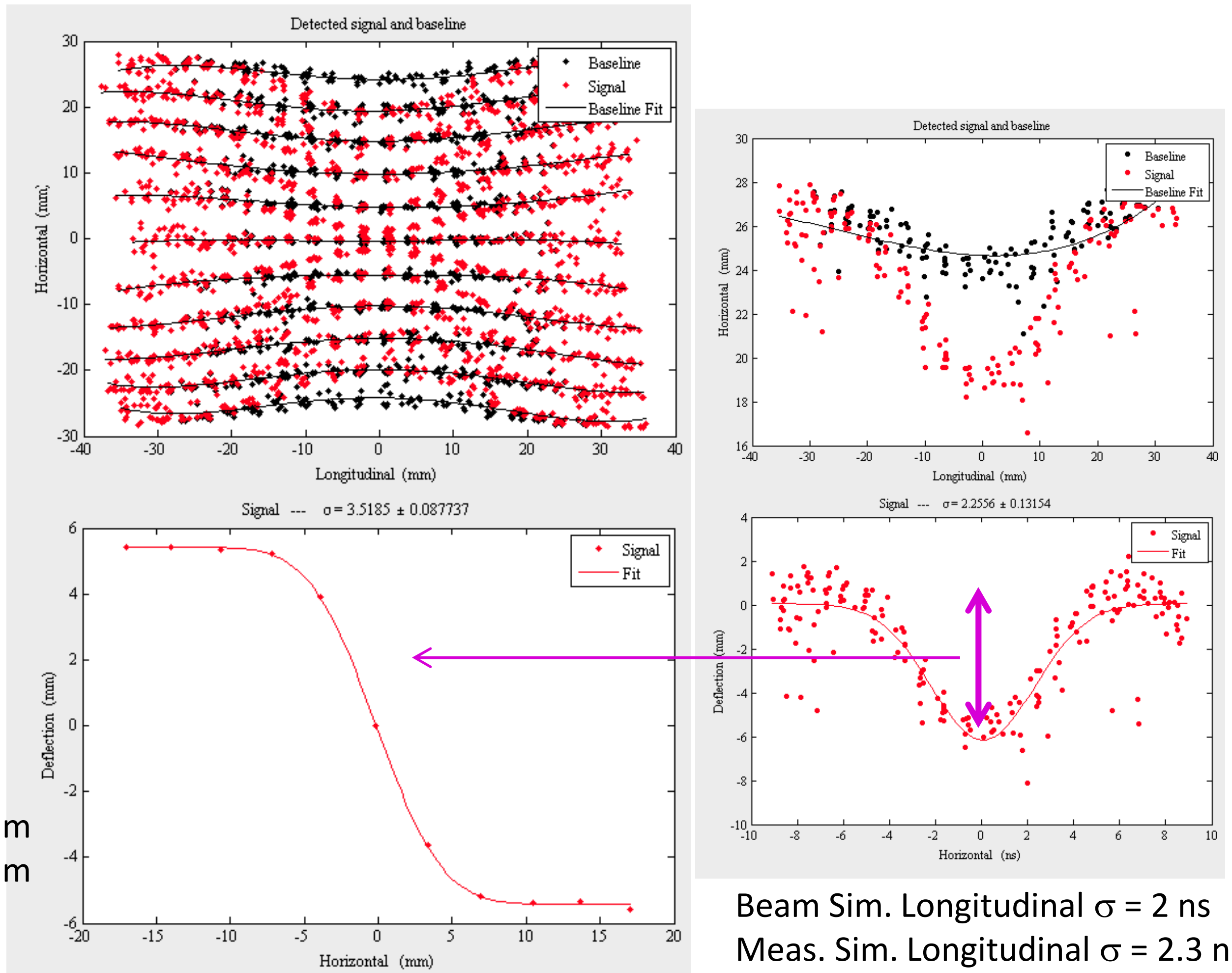



*Plots courtesy of Wim Blokland*

# Alternative Deflection Scheme




- Sweep the electron beam along the proton bunch
- Sweep duration coincides with the duration of the proton bunch

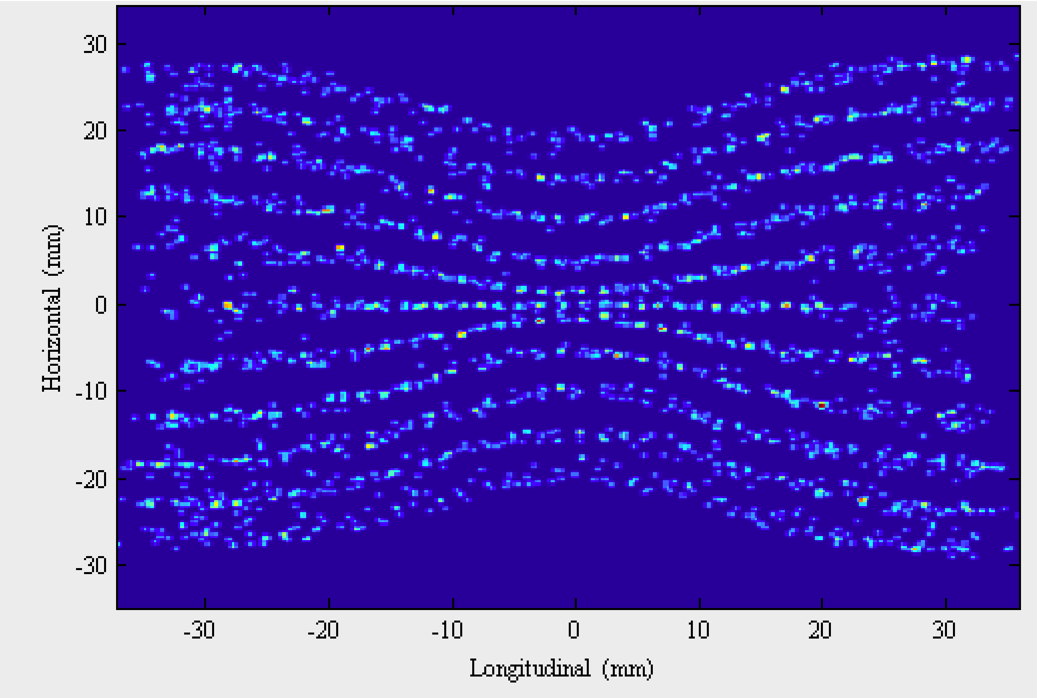



Beam Simulated Transverse σ = 3 mm
Meas. Simulated Transverse σ = 3.5 mm

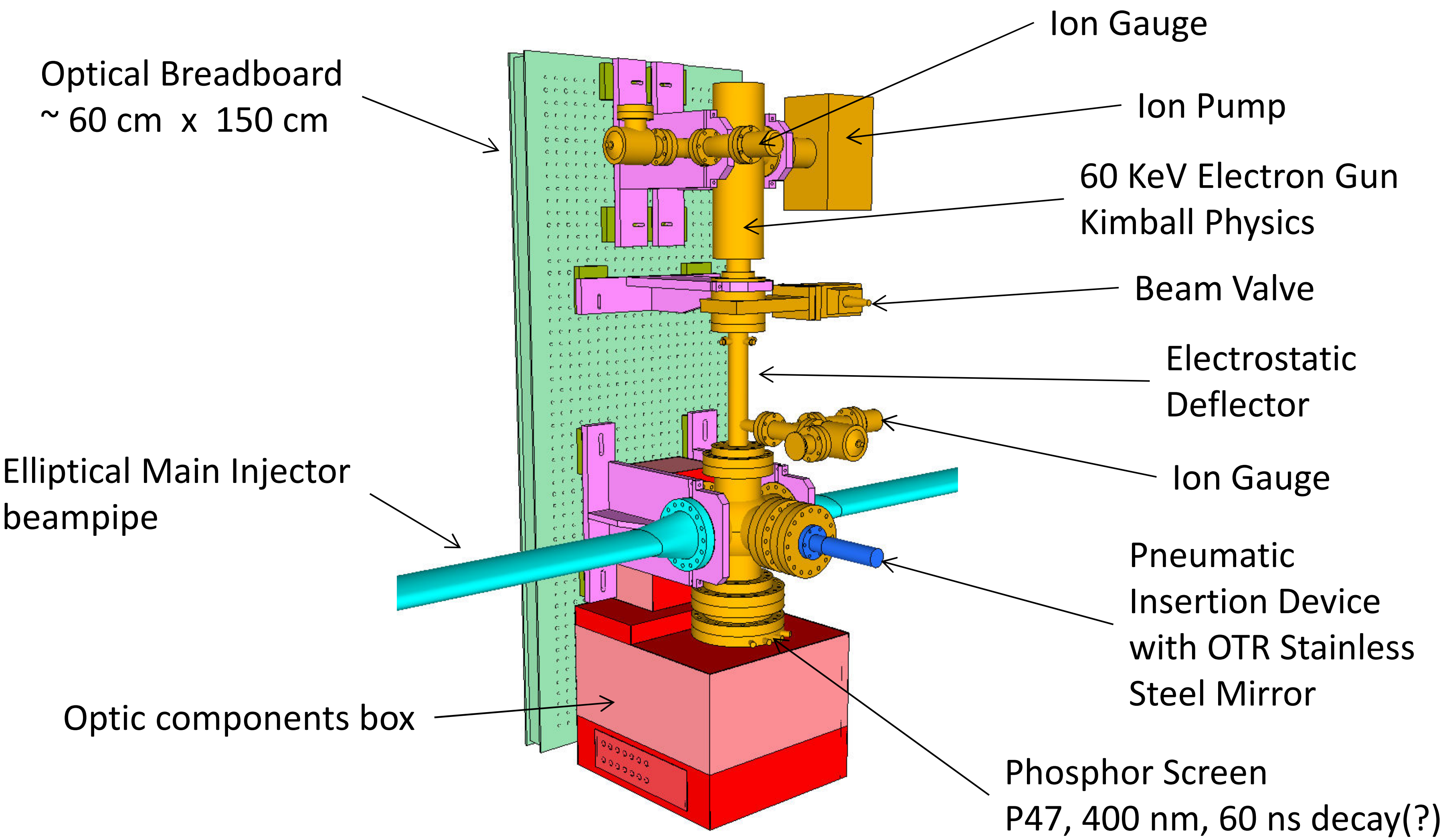
Beam Sim. Longitudinal σ = 2 ns
Meas. Sim. Longitudinal σ = 2.3 ns

# Simulated Camera Image

- Camera frames are ~30 ms
- Main Injector cycle is ~1 s
- Need to step many times per frame to accumulate data fast enough for measurement
    - Complicated to extract each step

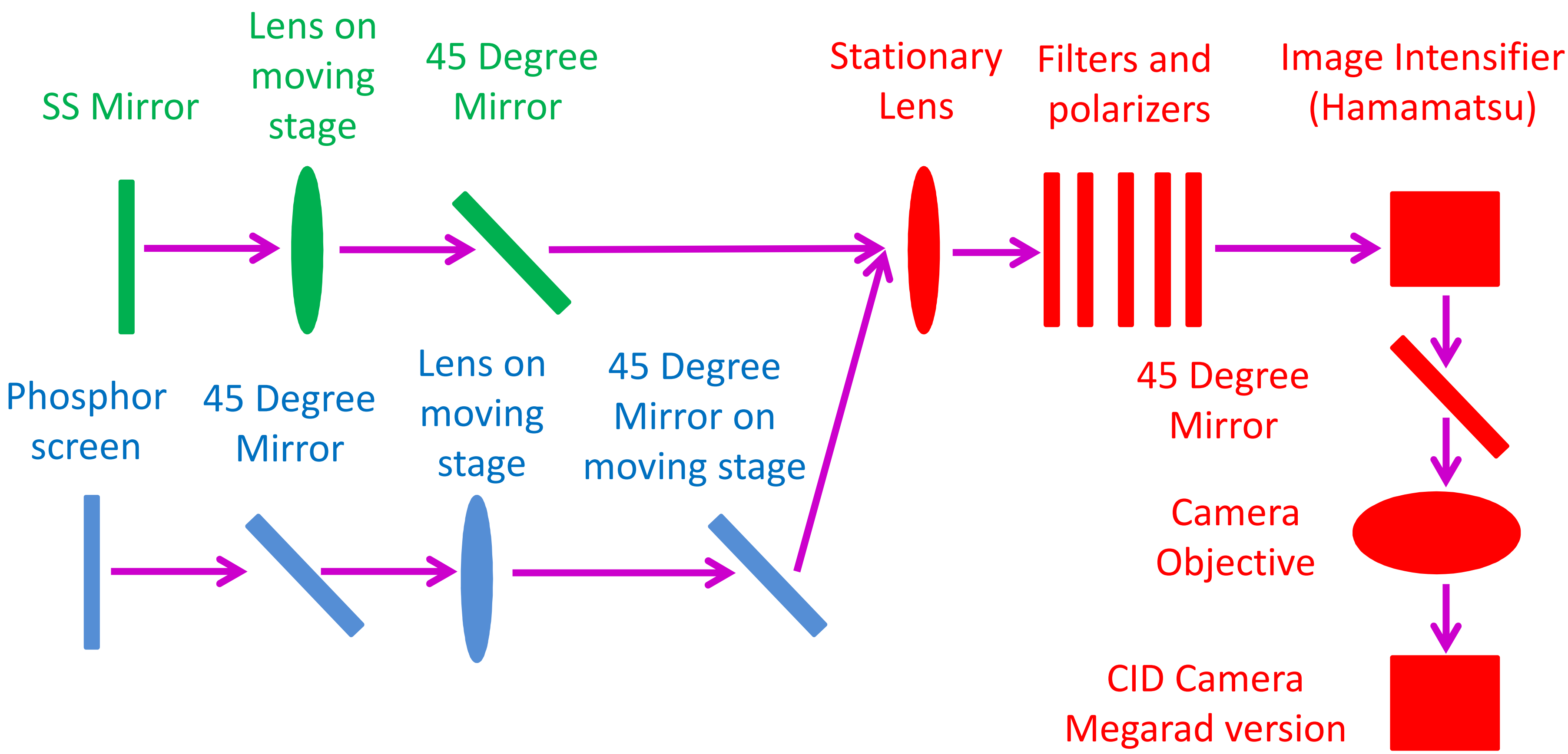


# Electron Beam Device



# Optics

Two optical paths: OTR screen and Phosphor screen with some shared elements
OTR screen is inserted at location of proton beam (sans proton beam) and used to focus the electron beam and measure the electron beam spot size



# Devices

Kimball Physics up to 60 KeV
(we will use up to 15 KeV)
6 mA, pulsed, 1 $\mu$s to DC
$LaB_6$ cathode, 100 $\mu$m spot size

15 cm long ‘circular’ plates
~2.5 cm diameter

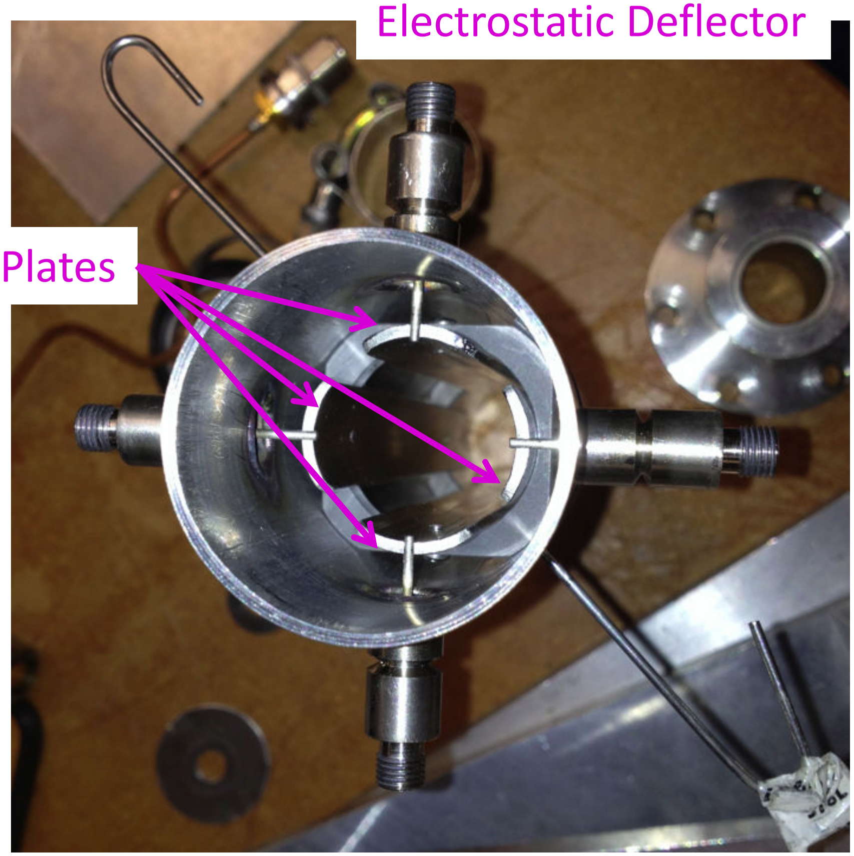
Thermionic Electron Gun

Solenoid and
steering magnets

Cathode

Electrostatic Deflector

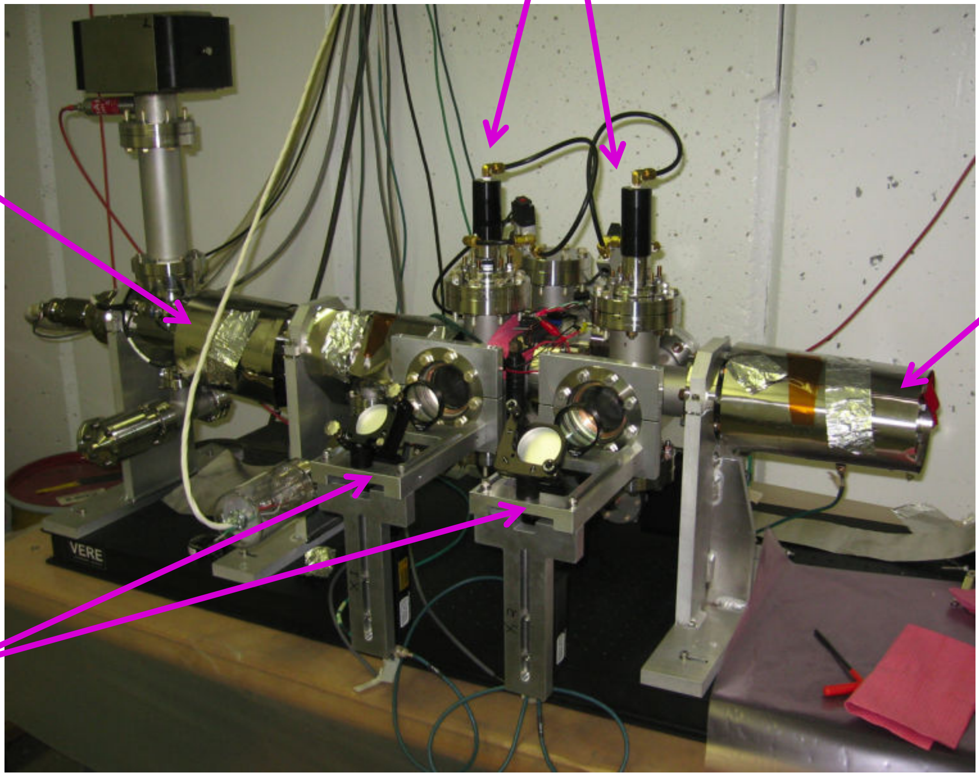
Plates



# Test Stand at NWA

Optical Transition Radiation Screens

Electron Gun



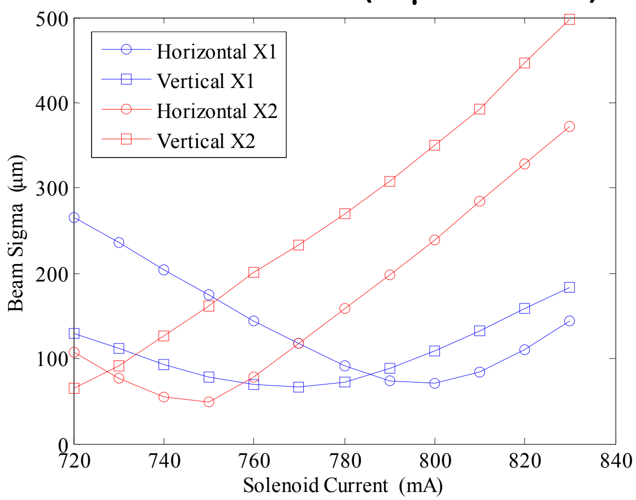
Faraday Cup

Lens / Digital Camera Imaging Systems

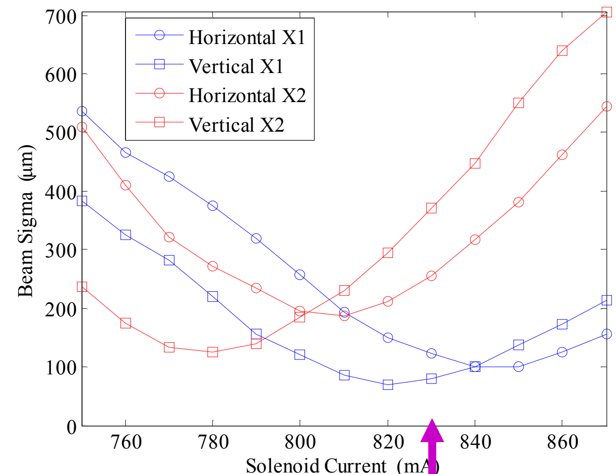
# Gun Tests

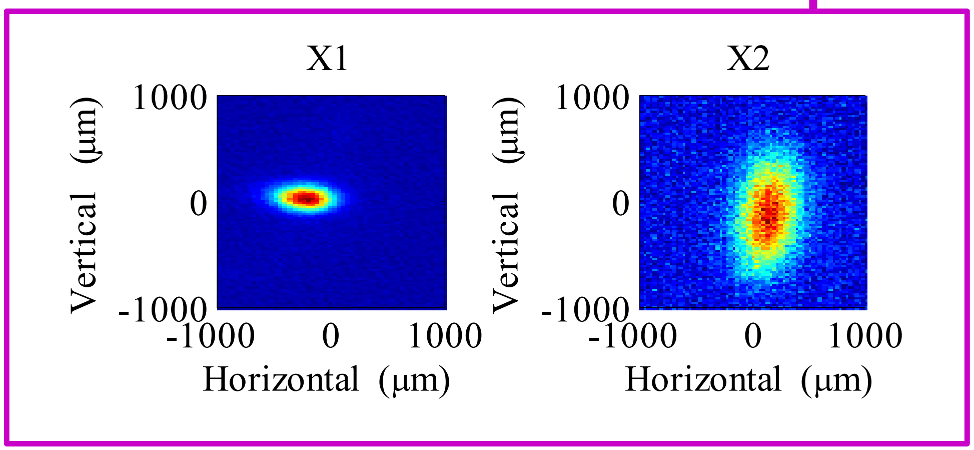
- Gun has internal solenoid
  - Scanned beam through waist at first screen

Scanned beam sizes from Ce:YAG screens (1 μA beam)



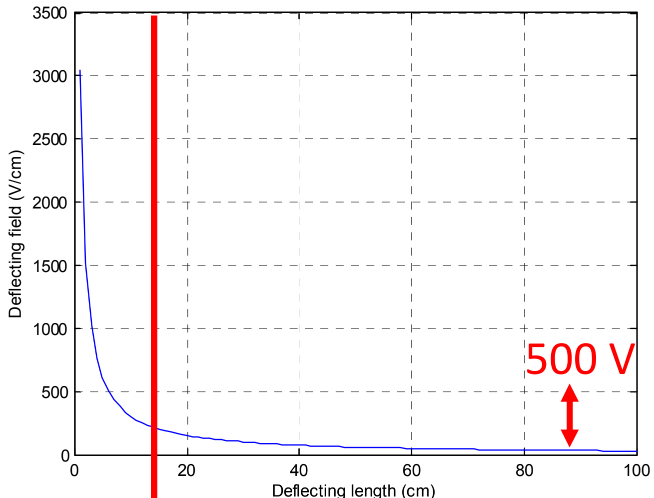

Scanned beam sizes from OTR screens (1 mA beam)



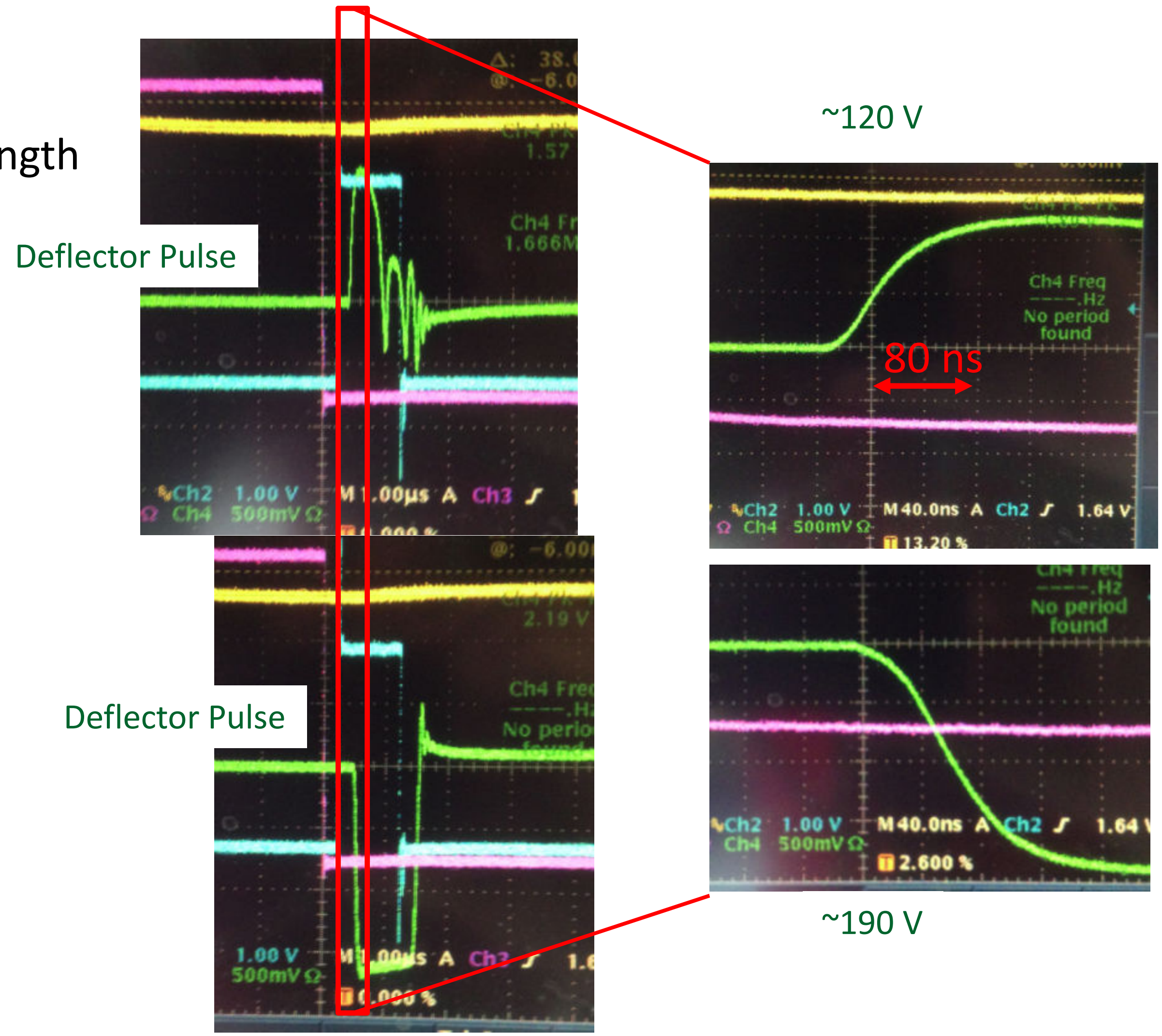



# Test of Electrostatic Deflector

Deflecting Voltage vs. Deflector Length

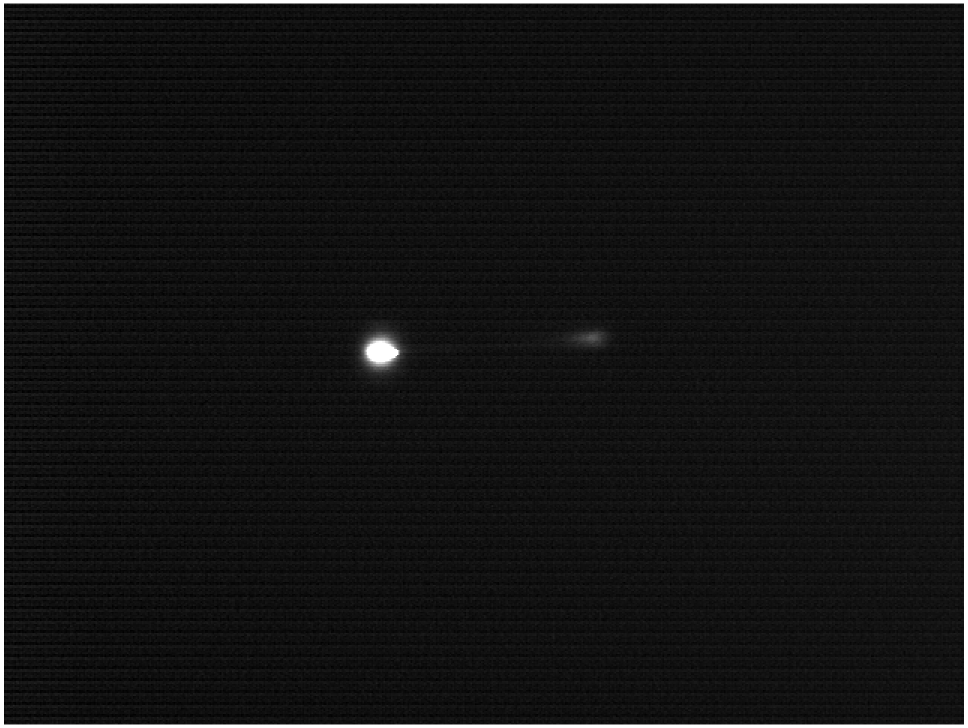



15 cm long plates

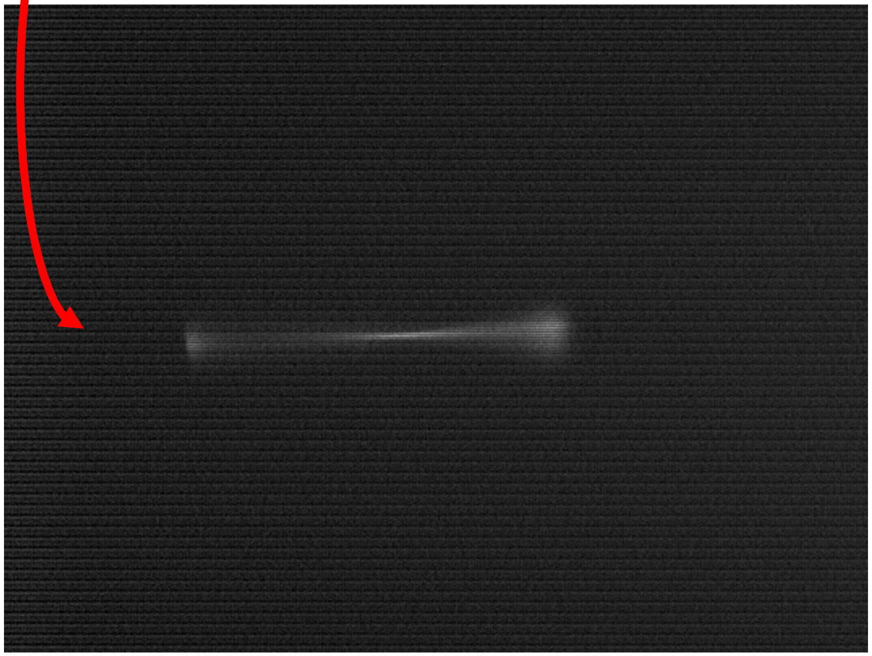


# Electrostatic Deflector Test

Short sweep
- Effect is similar proton bunch passing by

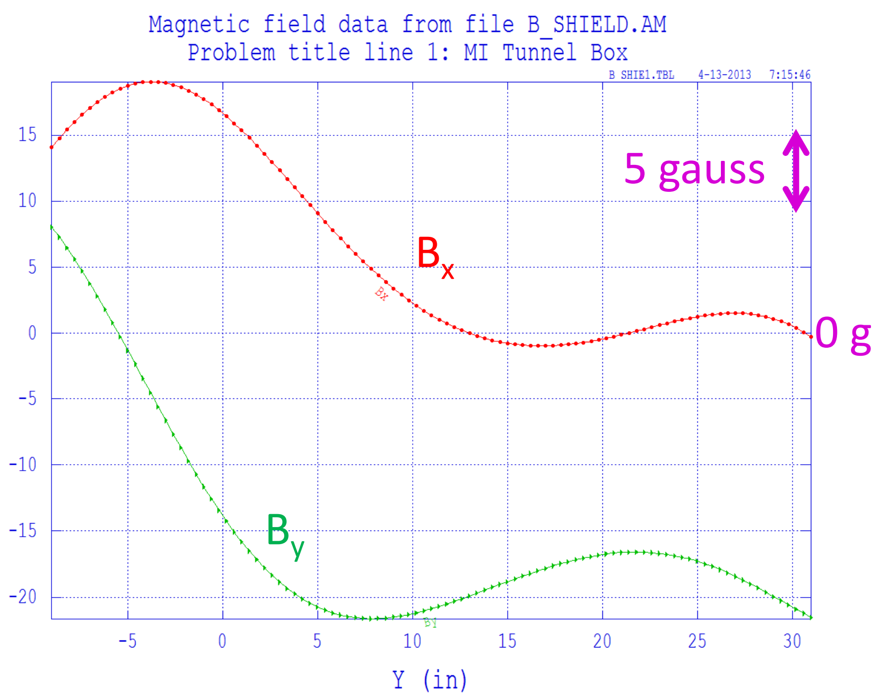


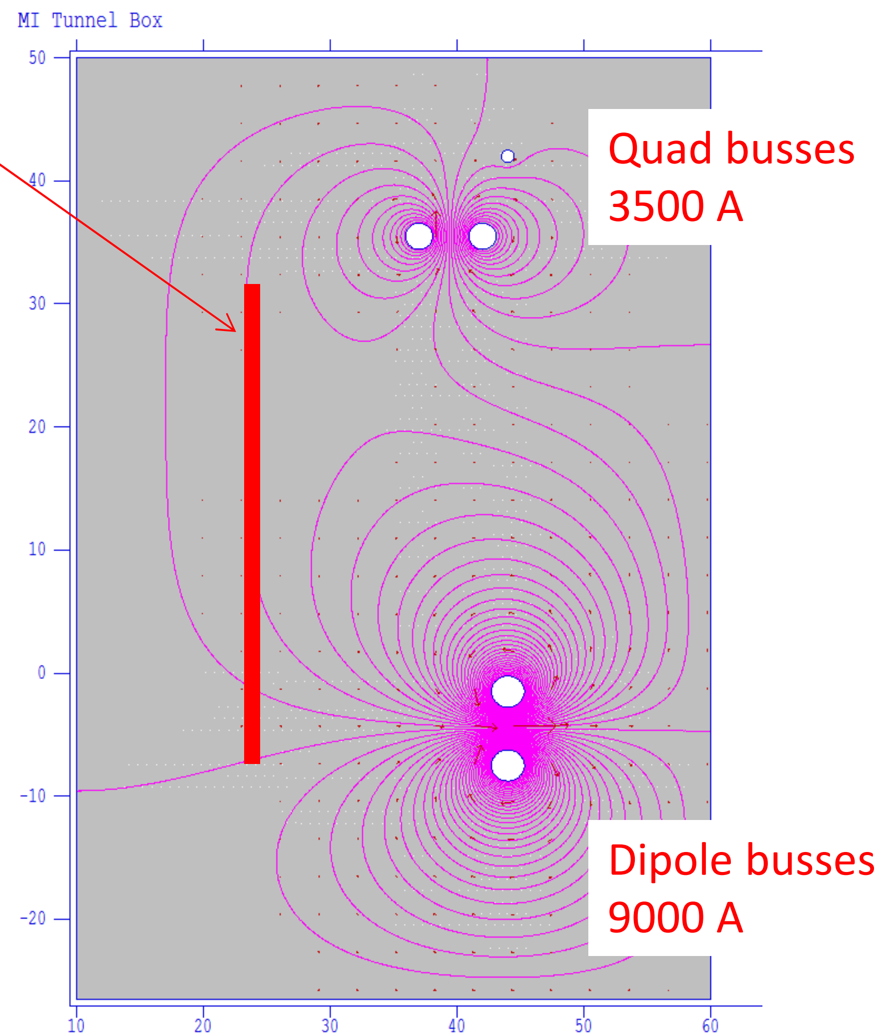
Longer sweep
- Bright part off screen
- Beam size not uniform
    - Possibly due to poor pulse quality



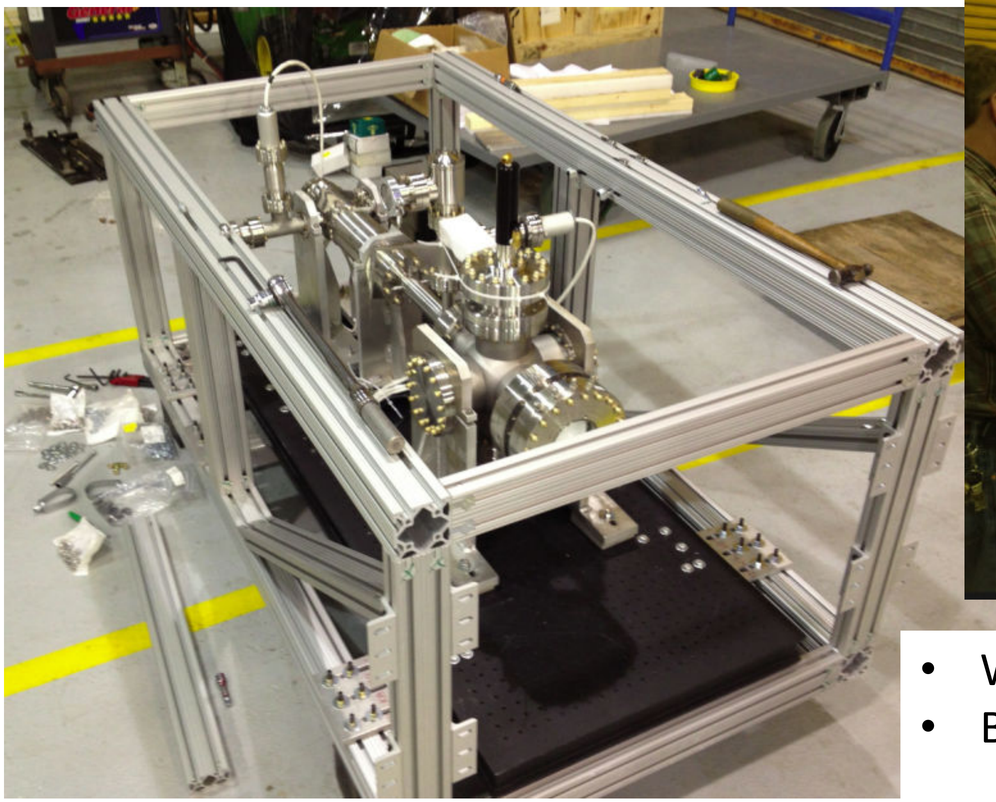
# Magnetic Fields in Tunnel

Need to shield beamline
First attempt will be mu metal



# Electron Beam Profiler



- Would like to install as soon as possible
- But…
  - Priority is “Very Low” (to put it politely)
  - Relies on the “kindness of strangers”

# Strangers (and not so strangers)

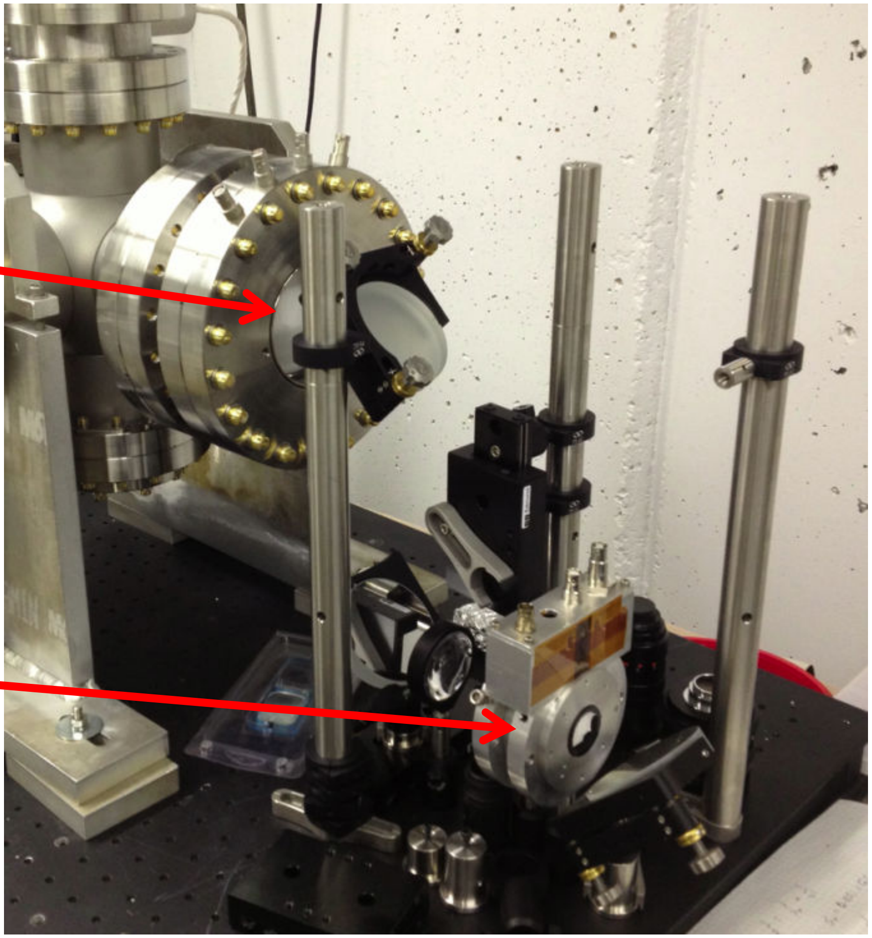
- Instrumentation
  - Amber Johnson, Carl Lundberg, Jim Galloway, Jim Fitzgerald, Peter Prieto, Pierpaolo Stabile, Andrea Saewart, Dave Slimmer, Dehong Zhang, Brian Fellenz, Alex Lumpkin
- Mechanical Support
  - Wade Muranyi, Brad Tennis, Elias Lopez, Debbie Bonifas, Scott McCormick, Ryan Montiel, Sali Sylejmani, Tom Lassiter, James Williams, John Sobolewski, Matt Alvarez, Kevin Duel
- Summer Students
  - Paul Butkovich, Khalida Hendricks, Danila Nikiforov
- Others
  - Charles Thangaraj, Dave Burk, Dennis Schmitt

# Extras

# Optics

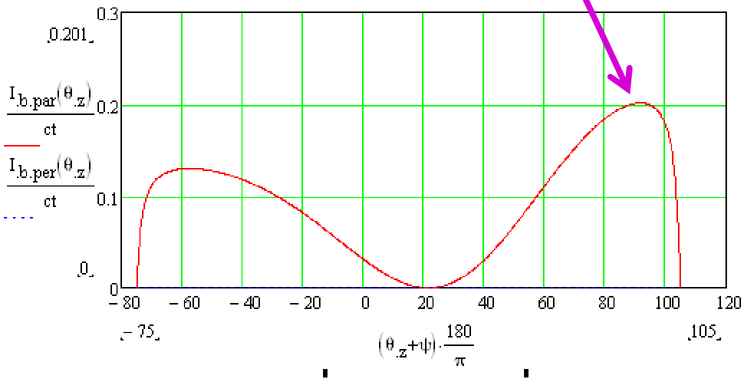
Phosphor screen

Image Intensifier



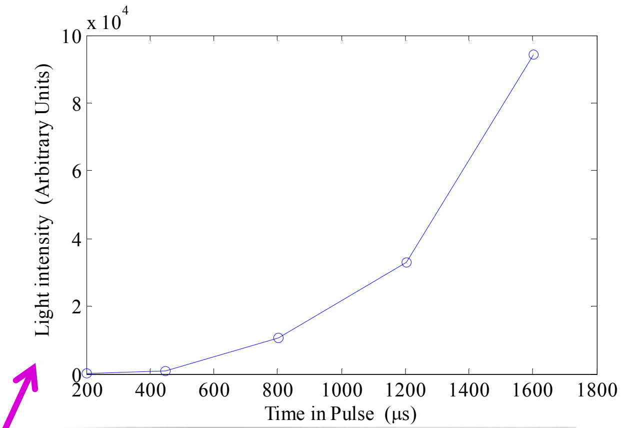
# Optical Transition Radiation

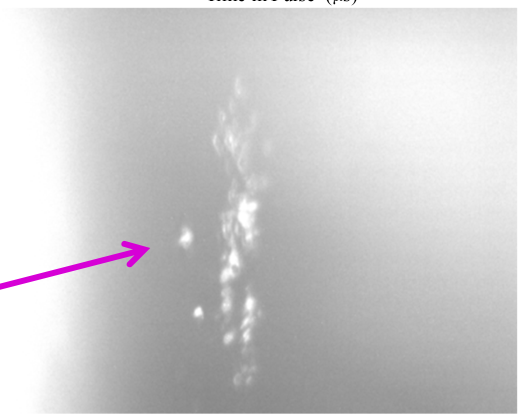
- Electron energy low
  - Broad angular distribution
  - Mirror should be 15° instead of 45°



(E. Bravin, private communication)

Light yield over the 2 ms electron pulse



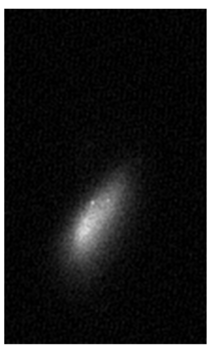



- Initial beam images determined to be blackbody
  - No polarization
  - Intensity increased nonlinearly with duration
  - Damage to stainless steel mirror observed

# Wire Tests

- Wire to simulate proton beam
- e Beam pulsed on for 40 μs
- Wire pulsed for 20 μs
- Half the time the beam is deflected

0V

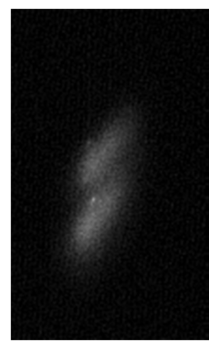


50V

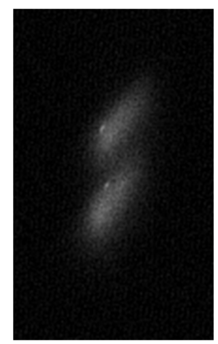
100V

150V

200V



250V



300V